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SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 6, NDRC

VOLUME 15

Underwater Sound Equipment II

ECHO-RANGING SYSTEMS

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 6
JOHN T. TATE, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on request from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Directors of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separte volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Any great cooperative endeavor must stand or fall with the will and integrity of the men engaged in it. This fact held true for NDRC from its inception, and for Division 6 under the leadership of Dr. John T. Tate. To Dr. Tate and the men who worked with him—some as members of Division 6, some as representatives of the Division's contractors—belongs the sincere gratitude of the Nation for a difficult and often dangerous job well done. Their efforts contributed significantly to the outcome of our naval operations during the war and richly deserved the warm response they received from the Navy. In addition, their contributions to the knowledge of the ocean and to the art of oceanographic research will assuredly speed peacetime investigations in this field and bring rich benefits to all mankind.

The Summary Technical Report of Division 6, prepared under the direction of the Division Chief and authorized by him for publication, not only presents the methods and results of widely varied research and development programs but is essentially a record of the unstinted loyal cooperation of able men linked in a common effort to contribute to the defense of their Nation. To them all we extend our deep appreciation.

Vannevar Bush, Director
Office of Scientific Research and Development

J. B. Conant, Chairman
National Defense Research Committee

FOREWORD

THIS REPORT, Volume 15 of the Division 6 Summary Technical Report, describes the work undertaken to improve the operation of the type of echo-ranging system employed almost exclusively during World War II. While the U. S. Naval Research Laboratory had, prior to 1941, developed effective echo-ranging equipment, time and experience in its use indicated that in certain respects its performance could be substantially improved. The problem presented to the Division was very analogous to problems in industry where continuous effort is made to improve upon already effective apparatus or assemblies. The Division also clearly realized that, as in industry, it is not enough that a certain modification should be of proven worth, but that in its introduction, production schedules must be considered, and the necessary steps be taken that maintenance and operating personnel become fully acquainted with the modified equipment. In some respects, it is a simpler process to introduce into service an altogether new type of gear than to introduce, with overall effectiveness, substantial modification in gear of a type already in wide service use. What the Division was able to accomplish was to demonstrate the value of certain modifications which could be gradually adopted in the redesign of sets being produced by manufacturers, and second, to design certain assemblies which could be attached to sets already in service or going promptly into service. It is believed these steps led to a gradual improvement in performance. In this connection, it must be emphasized that to a very substantial extent, technical credit for securing more efficient echo-ranging sets must be shared by the Division with the Navy and its contractors—the Submarine Signal Co., the Bell Telephone Laboratories, and the Radio Corporation of America.

This work was undertaken in close cooperation with the Navy. In addition to furnishing, initially, certain general facilities necessary to undertake this program, the Navy, as work progressed, made available additional test facilities. It is particularly appropriate to record the Division's appreciation of the constant support and encouragement given to those engaged on the project by Captain Rawson Bennett, Jr., of the Bureau of Ships.

The preparation of this summary report has required considerable effort and the Division appreciates the willingness of Mr. J. S. Coleman to undertake the task of assembling the material and presenting it in acceptable form. The technical development program was, in large part, assigned to the Division's New London and Harvard laboratories, and it is felt their performance deserves special mention. The services rendered by the Underwater Sound Reference Laboratories in the testing of sonar apparatus for NDRC and Navy agencies attempting to improve its efficiency should also be acknowledged. Of prime importance were the steps taken by the San Diego Training Group and others to assure that operating personnel could use effectively gear of the modified type. Equally important as a means of securing proper maintenance were the efforts of the Field Engineers assigned to the Bureau of Ships.

JOHN T. TATE
Chief, Division 6

PREFACE

THE PART played by the NDRC laboratories in developing "searchlight" echo ranging systems of the type described in this volume was largely one of improvising and modifying existing designs. Although in some cases complete systems were developed, they borrowed component designs from standard gear whenever possible. As a consequence, this volume, which describes only the activities of Division 6 in this field, cannot be considered as a text on the subject of echo ranging systems. It should, however, be useful for purposes of reference, supplementing other published works.

The material in the volume was, for the most part, compiled from individual laboratory completion reports and memoranda which, together with pertinent related documents, are listed in an inclusive bibliography to be found at the back of the volume. Although an attempt has been made to unify the presentation, the several chapters must still reflect somewhat the detail and style of the individual laboratories reporting. These laboratories include the Columbia University Laboratory at New London, Connecticut [CUDWR–NLL], the University of California Laboratory at San Diego, California [UCDWR], the Harvard University Laboratory at Cambridge, Massachusetts [HUSL], and the Bell Telephone Laboratories [BTL].

Editing and processing were carried out for Division 6 by the staff of the Summary Reports Group of Columbia University with the valuable assistance of J. W. Horton.

JOHN S. COLEMAN

CONTENTS

Chapter 1

INTRODUCTION

SONAR SYSTEMS in which observations are made of underwater sounds radiated by target vessels are described generically as direct-listening systems. Those in which the target is caused to become a secondary radiator, or reflector, of acoustical energy are known as echo-ranging systems. Observations made by means of the earlier and more elementary echo-ranging systems have many features which are analogous to those found above the surface when using searchlights. The modifications and improvements of this type of echo-ranging system are described in this volume. The more recent scanning sonar systems[a] operate with sound waves in a manner similar to that by which radar operates with electromagnetic waves.

Any naval vessel acts as a primary radiator of electromagnetic waves only by deliberate intent or by unusual accident. Such radiation may, in general, be avoided if necessary or desirable. Light and radar waves force the surface target to become a secondary radiator. To escape these revealing radiations the submarine was designed to operate beneath the surface of the sea. Through the development of echo ranging the possibility of employing secondary radiations is regained by those attempting to combat the submarine; although the submarine may find occasional security in acoustical shadow zones, caused by the presence of temperature gradients in the water, there appears to be no refuge where it may escape all means of observation.

Although anxious to remain invisible the submarine finds it necessary, by means of its periscope, to retain some degree of contact with this medium. Were it not for this contact the submarine would itself be unable to carry out its own enterprises. Although when using its periscope the submarine risks observation to observe, the advantage has, until recently, been greatly in its favor. The development of radar has extended the limitations imposed by human vision and thereby restored the balance to some extent. In consequence the submarine is now forced to operate more completely and more continuously beneath the surface. Thus the need for some subsurface vehicle for observational data is more imperative than ever before. The advent of radar has, in this sense, increased rather than diminished the need for sonar in subsurface warfare for both the surface craft and the submarine. The submarine went below the surface that it might see without being seen; unless it can also hear without being heard it will have gained a questionable advantage.

[a] Described in Division 6, Volumes 16 and 17.

1.1 SCOPE OF DIVISION ACTIVITY

At the time of the formation of Section C-4, later to become Division 6, echo-ranging equipment capable of good performance was available in limited quantities. In view of the urgent need for large quantities of serviceable gear to equip the expanding Navy, it was decided to avoid delay by concentrating on expanding the production of existing and proved designs. The section and its laboratories, in turn, concentrated upon a program of improvements calculated to facilitate maximum performance of these standard equipment types. As a result a number of auxiliary circuits and components were designed and constructed which were quickly adaptable to existing shipboard installations. Such modifications included methods for increasing the accuracy and ease of obtaining bearings, for improving the ability of the system to discriminate the target echo from background noise, and for reducing operator fatigue. These and parallel developments were all aimed at raising the performance level of the average sonar operator under typical operational conditions. An account of these developments is presented in some detail in succeeding chapters.

1.2 THE ECHO-RANGING METHOD

The functional operation of a conventional echo-ranging system is simple as far as the basic elements are concerned. An electric wave of supersonic frequency is generated in an elec-

tronic oscillating circuit. This circuit is connected to the transducer for a short interval of time to produce a focused pulse of supersonic acoustical energy in the water. Once the pulse has been transmitted, the transducer is disconnected from the output of the electronic generating circuits and connected to the input terminals of a sensitive receiving amplifier. The same characteristics of the transducer which directed the pulse along a given bearing now restrict reception to the neighborhood of that same bearing. A returning echo produces a response in the output of the receiving amplifier and thus indicates the presence of a reflecting target. Further, the time interval between pulse departure and echo arrival may be measured and the range of the target thus determined. Repeated transmissions obtain quantitative data on the rates of change of both bearing and range. From these the course and speed, as well as the position, of the target may be estimated. This ability to determine the range of a silent submerged target is a unique characteristic of echo ranging.

1.3 ECHO RANGING VERSUS LISTENING METHODS

Range and Bearing

There are other operational differences between echo ranging and direct listening in which the advantage is not so completely on the side of echo ranging. Both techniques are capable of determining the bearing of any target with adequate accuracy. In the case of a target radiating a detectable sound wave, range may also be determined by direct listening, although with less accuracy than by echo ranging. This involves the use of crossed bearings from two points separated by a known base line having the dimensions of a single vessel. In single ship installations, however, the range accuracy possible with direct listening varies with target bearing, the range becoming indeterminate along the bearing of the base line.

Search Operations

When conducting search operations by means of echo-ranging transmissions, the rate at which a given small sector may be scanned is significantly less than with direct listening. With echo transmissions it is necessary to cover a single bearing long enough for energy to be propagated to the limiting range and back to the transducer. When searching for a noisy target by direct listening, any sector of interest may be scanned as rapidly as desired. This advantage of direct listening does not, however, extend to the rate at which large areas of the ocean may be patrolled. The range of possible detection by direct listening, however, decreases rapidly as the speed of the listening vessel is increased. This is because of the increased intensity of masking noises due to water and machinery. When searching by echo transmissions, the width of path covered may be less than with direct listening under quiet conditions, but the limitation on the ship's speed is the time required to complete a number of individual transmissions sufficient to cover the assigned path.

The limitation on search rate with the searchlight form of echo-ranging system constitutes a most troublesome handicap. A considerable portion of the effort expended on the development of sonar has been directed toward improving this situation. There is, of course, no means of avoiding the delay interval between transmission and the arrival of the echo. This is fixed by the velocity of sound progagation in water. While waiting for one signal, however, others may be dispatched or observed. Two such methods are embodied in what are known as scanning sonar systems.[b]

Ship Security

A tactically important difference between direct listening and echo ranging is that any vessel undertaking the latter operation becomes a primary radiator of supersonic energy and is consequently liable to detection. This is of particular significance in the case of submarines wishing to remain concealed. Fortunately for the submarine it is in a much better position to employ direct listening than is a surface craft. When submerged, submarine self noise which might

[b] Discussed in Division 6, Volumes 16 and 17.

mask target sounds from a distant source is negligible compared with that attending surface operation. Moreover, surface ships are likely to be comparatively noisy.

Maximum Detection Range

It is hardly reasonable to compare the detection ranges possible by direct listening and by echo ranging since, in many important cases, no detection is possible by listening methods alone; however, it must not be forgotten that the path length involved in echo ranging is twice that involved in direct listening and the total transmission loss is consequently twice as great. As the range increases, therefore, the energy which must be transmitted in order to obtain an echo of adequate strength increases very rapidly. At the present time, it is unusual to receive a satisfactory echo from a target more than 3,000 yd distant. Capital ships have frequently been detected by a listening submarine, while under way submerged, at distances in excess of 25,000 yd.

The differences in operational characteristics of echo ranging and direct listening emphasize the fact that any consideration of the application of sonar must take carefully into account the capabilities and limitations of each if the most effective solution to any given problem is to be reached. These matters are considered in more detail in our examination of the performance of echo-ranging systems and of the factors on which they depend.

1.4 OCEANOGRAPHIC FACTORS

The range at which a target submarine may be detected and the accuracy with which this range may be determined depend primarily upon the characteristics of the sound energy employed and its behavior in the ocean. Our knowledge of the characteristics and behavior of sound waves in sea water has been greatly extended during the recent war.

The minimum detectable energy level of a signal is determined by the character and magnitude of simultaneous background noise through which the signal must be detected. This is as true in echo ranging as in any other system. Valuable statistical data are now available on the intensities of sounds generated by ships of various types and on the spectral distribution of their energy. Sound waves in water due to other causes, such as waves, rain, and marine life, have also been analyzed and catalogued. In addition to being limited by interfering noise in the same manner as is direct listening, echo ranging may suffer serious interference from the reverberation following its own transmissions. This is merely another way of saying that it is sometimes difficult to distinguish between energy returned from a target of particular interest and energy returned from other reflecting surfaces. The phenomena of reverberation have been examined with some care and the limitations which they impose upon the performance of echo-ranging systems evaluated.[c] These studies have also provided a basis for the quantitative understanding of the role of the target in redirecting energy back toward the observation point.

Transmission Losses

The transmission of sound in the sea is influenced by several important factors. Its intensity decays as the distance from its source is increased due to the fact that the total energy is distributed over larger and larger areas. In addition, sound waves in water suffer a significant attenuation due to the actual dissipation and dispersion of energy by the medium itself. This attenuation loss is superimposed on the geometrical spreading effect, the two together being generally classed as transmission loss. Attenuation increases in almost direct proportion to the frequency and becomes of major importance at the higher supersonic region, virtually prohibiting the transmission to any appreciable distance of signals of 100 kc or higher. Transmission loss is always present; although it exhibits a decided variability, its average magnitude may be predicted within reasonable limits.

[c] A detailed treatment of this work will be found in Division 6, Volume 8.

Refraction of Sound

In addition to the normal transmission losses, underwater sound transmission is very seriously affected by refraction whenever the temperature of the water varies with depth. This refraction causes a bending of the sound waves from the path along which it was initially directed. In some cases the paths are so sharply curved that it is impossible to obtain an echo from a target only a few hundred yards distant. In other situations refraction may result in the establishment of what is virtually a sound channel. In such cases geometrical spreading does not take place in the normal manner. The result is that sound energy can be transmitted very long distances without serious loss in intensity.

It is now recommended practice to measure the vertical temperature gradient of the sea before attempting echo-ranging operations. Once this temperature gradient is known it is possible to predict, in a general way, maximum assured echo ranges. A knowledge of the temperature gradient existing at any time is equally pertinent to the navigation of submarines. So informed, it is possible for a submarine commander to determine the depth at which he is least likely to be detected by an enemy surface craft.

Reflection of Sound

Reflections from the surface or, if the water is not too deep, from the bottom, may result in the interference of sound waves arriving at a given point by paths of different lengths. Such interference appears as a change in the energy level and is responsible for much of the apparent variability of transmission loss.

Application to Engineering Design

All this information as to sound waves and their behavior applies practically to existing conditions commonly encountered in service. This type of data has great utility to those attempting to design equipment or to select a broad plan for meeting some specific tactical situation. For such problems it is quite as desirable to know the probable variability of those quantities which affect operation as to know their most probable average. Although there are numerous voids in the data available on the characteristics of underwater sounds and on their transmission, present knowledge is sufficient to serve as a reliable guide to engineering judgment and often discloses the probable limits to the performance of some contemplated system or technique. It is sometimes quite as useful to know what cannot be done as to know how to achieve an attainable objective.

1.5 METHODS OF IMPROVING PERFORMANCE

Transducer Directivity

Both piezoelectric and magnetostrictive transducers are particularly well adapted to supersonic frequencies which permit highly directional transducers having practical dimensions. The use of a directional receiving transducer provides an improvement in the signal-to-noise ratio by excluding all interfering signals except those which arrive along approximately the same bearing as the signal. The use of a directional transducer is one of the most powerful methods of reducing the interference of locally generated noises.

Operation at supersonic frequencies has the further advantage that noises of local origin contain relatively little energy in this region. The likelihood that an echo from a distant target will be obscured by local noise is, therefore, less at supersonic frequencies than it would be with transmissions at lower frequencies where much of the energy of noises caused by waves, ship motion, and machinery is concentrated.

Bearing Deviation Indicators

One modification, introduced during World War II, is the *bearing deviation indicator* [BDI]. The ability to determine the bearing of any detected target is, of course, implicit in the use of highly directional transducers. The accurate determination of bearing by this means

requires that the intensities of successive echoes be compared as the axis of maximum response of the transducer sweeps the location in question. This is time-consuming. There is also the difficulty of maintaining contact since no indication is available of the direction of bearing error. The BDI effects a marked improvement in this situation by showing, for every echo giving a readable signal, whether the target is to the right or to the left of the axis of maximum transducer sensitivity. This is accomplished by a modification providing two distinct output connections which give maximum responses at slightly different bearings. It is merely necessary to compare the signals from the two output connections to determine which of the two bearings is more nearly that of the target.

Receiver Bandwidth

An important method of reducing interfering noise without simultaneously reducing the signal is to restrict the response of the receiving system to frequencies characteristic of the signal components. This method is particularly effective in the case of echo ranging where the frequencies of signal components are, as already noted, restricted to a narrow band.

Automatic Gain Control

Attention has been directed to automatic control of the amplification, or gain, of the receiving amplifier circuits during the receiving portion of the operating cycle. This was attempted primarily to improve the working conditions of the operator. With receiving circuits having a fixed gain sufficient to provide adequate response for long delayed echoes, the initial response to local reverberation is likely to be so loud as to impair the ability of the observer to hear a faint echo. In any case it produces undesirable physiological strain.

As quantitative knowledge improved, it became possible to design methods of automatic gain control which compensated reasonably well for the increase in transmission loss with range. When such controls are applied, the response of the system, both to reverberation and to significant echoes, is more or less independent of range. The control of receiving gain is especially desirable with *plan position indicator* [PPI] presentations.

The Doppler Effect

One factor which appears with some prominence in supersonic echo ranging is the doppler effect. This effect describes the difference in frequency between a transmitted wave and a received wave whenever there is relative motion between the transmitting point and a reflecting target. In some cases this shift in the echo frequency may be most advantageous, because whenever a target vessel has a component of motion with respect to the water in line with the observing vessel, the echo frequency will differ from the average frequency of general reverberation. Because of this difference it may easily be detected at a much lower level than would otherwise be possible. Doppler shifts also provide the observer with means for deducing relative range rates.

The doppler effect also has a disadvantage in that it makes the use of extremely selective receivers generally infeasible. This is particularly true in the presence of large range rates, as occur in the case of a submarine operating against a high-speed surface vessel; thus, it is not surprising that both doppler enhancers and doppler nullifiers have been found useful.

Echo Indicators

It is generally necessary to employ some form of instrument which will make the signal perceptible to the observer. Water-borne sounds are generally transformed into airborne sounds so that they may be heard. It must be remembered, however, that the ability to interpret such sounds is an acquired facility. Normal experience has taught little regarding the significance of underwater sounds. Any form of instrumental response which may best aid the detection and identification of the signal may therefore be freely selected. In such a situation any endeavor to obtain "naturalness" may prove to be misdirected. The choice of the most suitable type of instrument for any given purpose is always a matter of intelligent judgment.

For detecting the echo from a distant submarine no instrument has yet been found which is more generally reliable than those in which the signal is perceived by the ear of an observer especially trained for the task. The ear may be aided materially by the eye if the signal is presented in a visible form as well as in an audible form. When using sight and hearing simultaneously the observer is more alert, his perception more acute and less subject to irrelevant distractions.

As a visual aid to the early detection of weak signals, a cathode-ray oscilloscope having a persistent screen is perhaps the most suitable type of indicator. This pattern is retained for a short time and therefore supplements the memory of the observer.

Some form of visual indication is essential in measuring and giving a record of the time interval required for an echo signal to travel to the target and back. In the majority of echo-ranging systems the automatic control of the transmitting-receiving cycle and the visual presentation of elapsed time or range are in a single convenient instrument. The chemical sound range recorder has proved a most useful instrument for this purpose. This recorder, by means of an electrochemical stylus, traces a line of variable density corresponding to the signal level across a slowly moving paper tape for each successive transmitting-receiving cycle. The rate of change of range of any target returning a succession of echoes is here determined from the slope of a line through the adjacent echo traces. The instrument is provided with scales and with mechanical devices to assist in determining the correct firing time for various types of subsurface ordnance.

Instruments arranged to give a plan position indication are also used in connection with some sonar systems. Scanning systems universally employ this form of presentation although it is sometimes desirable to supplement it with some other type of presentation from which the range of a single target may be read more conveniently and more accurately. Plan position indications have also been used with the more elementary arrangements of echo-ranging equipment. They are of particular utility in adapting the echo-ranging gear to the detection and location of multiple targets as in the case of mine fields.

Mechanical Features

The mechanical features of echo-ranging equipment are by no means the least important of its operating characteristics. Conditions encountered in surface ship operations are largely unfavorable to the operation of echo-ranging equipment. The transducer should be as far outside the hull as is practical in order to reduce locally generated noise and to avoid distortion of the sound beam. The transducer and its supports must therefore be sufficiently rugged to withstand the strains imposed by the water at high ship speeds. Also, this motion through the water causes turbulence and cavitation around the transducer which produce high self noise at all except low speeds. This may be partially reduced by enclosing the transducer in a streamline housing which removes it from immediate contact with moving water. The use of such housing, or dome, obviously increases the complexity of the structural and acoustic design problem.

Maintenance of True Bearing

The fact that a highly directional transducer is mounted upon a moving vessel obviously makes it more difficult to keep it trained upon some target than would be the case were it operated from a fixed platform. It is apparent that the transducer axis will be deflected from its assigned bearing both by roll and pitch of the vessel and by any changes in course. To relieve the operator of the burden of continuously checking the ship's course and applying suitable training corrections, systems have been devised whereby automatically applied corrections place the transducer training on a true bearing rather than a relative bearing basis. This is accomplished by the *maintenance of true bearing* [MTB] system. Serious consideration has also been given to the incorporation of gyroscopic stabilization of the vertical axis to permit the training of the transducer to be referred to the true vertical rather than to

an axis varying with the roll and pitch of the vessel.

Depth Determination

With the increased depth of submergence now attainable by modern submarines, subsurface warfare calls for three-dimensional navigation. It is inevitable that the acoustical axis of future echo ranging transducers must be trainable in elevation as well as in azimuth. This is required to maintain contact during close approaches and to provide a means for determining the depth of submergence as well as the horizontal position of the target. The principle has been shown to be entirely possible by several experimental installations. It remains to make the technique generally applicable under service conditions.

1.6 OTHER APPLICATIONS

There are other important applications of echo ranging. By far the most common is in the echo sounding fathometer by which the depth of water beneath a ship is determined in the same manner as is the range of a submerged target. The fathometer is now almost universally used by commercial vessels as well as by naval craft and is coming to be as familiar a fixture in the pilot house as is the compass.

Mine Detection

Echo ranging has recently proved to be of considerable utility in the detection of submerged mines by submarines, either submerged or on the surface, and of obstacles to landing operations. While the distance at which a small mine case may be detected with reasonable certainty by echo ranging in shallow water is somewhat limited, echo ranging has, nevertheless, proved adequate for establishing the positions of mines in operations which could not be avoided regardless of the hazard. Considerable diversity, both in operational requirements and in environmental conditions, is to be expected in sonar applications as varied in purpose as those just mentioned. While it is true that certain fundamental principles apply in general to all applications, it is evident that the detailed solution of any given problem must take fully into account the unique conditions encountered. In military and naval activities, operational requirements may change on short notice and in an unpredictable manner. It is always desirable that any new technique required be implemented for combat service with the least delay. This suggests a design policy under which certain flexible aparatus units perform the basic functional operations and any specialized operations are confined to supplementary elements.

Coastal Surveying

Underwater sound transmissions are also used to measure the distances between fixed points in coastal surveys. Distances may, in this case, be evaluated in terms of the difference in travel time between radio waves in the ether and simultaneously transmitted sound waves in the water. Since the sound traverses a single, direct path, much greater ranges are possible by this method than by echo ranging. It is common practice to generate the sound waves required in radiosonic ranging by means of small explosive charges. Partly because the energy thus available is so great and partly because a single transit of the distance is involved, ranges of more than 100 miles are not uncommon.

Chapter 2

GAIN COMPENSATING CIRCUITS FOR SONAR RECEIVERS

2.1 INTRODUCTION

THE DEVELOPMENT of gain compensating circuits for sonar receivers was initiated to reduce the adverse effects on operator efficiency caused by the initial blast of reverberation following each ping. A number of circuits have been devised which effectively reduce the gain of the receiver during the initial blast of reverberation and then restore it in time to receive the echoes.

The term reverberation, as used in echo ranging, refers to the reflected sound, other than that from the target, which returns to the projector. The nature of the reverberation in a given instance depends on the transmitted power, on the length of the ping, and on the underwater "auditorium." Usually the reverberation level reaches a peak immediately following the ping, and then it decays in a manner and at a rate which vary with water conditions.

One characteristic of reverberation is that its pitch is usually the same as that of the primary signal. Unless the desired echo has an appreciable doppler shift, the operator must distinguish target echo from reverberation chiefly on the basis of tone quality and relative intensity. Since the intense blast of reverberation which follows each ping persists at a masking level for a time corresponding to ranges up to 500 yd, the nervous and auditory systems of the sonar operator face considerable punishment.

To improve the efficiency of the operator, several types of gain-control circuits have been incorporated into sonar gear. The first to be developed was *time-varied gain* [TVG]; this was followed by *reverberation-controlled gain* [RCG] which found general use with standard American sonar equipment. For purposes of comparison, a description is included of the British *automatic gain control* [AGC].

With TVG, the operator bases his selection of the initial reduction in gain, with its corresponding time interval before return to maximum sensitivity, upon his determination of the prevailing reverberation conditions and upon the desired echo range. If the TVG characteristics are improperly chosen, the echo may be lost. Despite this disadvantage, various TVG circuits were developed both for application to sonar equipment already in service and for incorporation in the design of new equipment. TVG was superseded by the more effective RCG circuit.

The RCG system automatically reduces the amplifier gain by an amount determined by the initial reverberation level, and then restores the gain at a rate determined by subsequent reverberation. The RCG is essentially a unidirectional gain compensating control. It reduces the likelihood of losing desired echoes, which was a disadvantage of TVG, and nearly eliminates the need for repeated adjustment of receiver sensitivity controls. However, if the reverberation should increase after its initial fall, as may occur in shallow-water echo ranging, the gain remains at the level it had before the reverberation increased again. As a result, the operator, who hears the increase as an actual increase in receiver output, may confuse it with increases in output which arise from true target echoes.

The *automatic gain control* [AGC] used in British Asdic AVC receivers is similar to the RCG circuit in that the degree of gain reduction in each instance is determined by the prevailing level of reverberation. An advantage of the AGC system over the RCG is that in shallow-water echo ranging the circuit automatically discriminates between the slow rises in input due to increased reverberation and the sudden rises due to echoes. In some cases, however, it is a disadvantage to have the clipping effect of this type of gain reduction obscure the indication of the pulse duration. Provision is also made in the AGC system for a rapid restoration of amplifier gain at the termination of the echo pulse, to permit recognition of a second echo closely following the first.

Time-Varied Gain

Time-varied gain [TVG] is an automatic volume control circuit used to control the gain of a sonar receiver for a given period following the emission of a ping. It reduces the receiver output to a comfortable level during reception of the initial blast of reverberation, thus protecting the operator from a high-level signal, and restores normal sensitivity before arrival of the target echoes. Any of several TVG characteristics may be selected by the operator to correspond to prevailing reverberation conditions and to target range.

The TVG circuit was developed by the Harvard Underwater Sound Laboratory, Cambridge, Massachusetts [HUSL] for application to sonar equipment already in service and for incorporation in new equipment, prior to the completion of the more effective RCG circuit.

2.2 PRINCIPLES OF TVG OPERATION

General Description

With TVG, control of gain with time is accomplished by charging a condenser with negative potential during transmission of the pulse and then discharging this condenser, following the ping, through a shunt resistor. The exponentially decaying bias, applied to one or more of the remote cutoff tubes in the listening amplifier, varies the gain to provide a fairly constant reverberation level.

TVG action is a function of two factors: (1) the initial voltage to which the bias control condenser is charged, and (2) the rate at which the condenser discharges. If these are properly adjusted, the audible reverberation remains substantially constant at a level which the operator may select with the manual gain control. An adequate amount of reverberation remains to provide a reference tone for recognizing target doppler shifts. An equal opportunity is provided throughout the listening interval for recognition of any echo which rises above the then-prevailing reverberation background. A disadvantage of TVG is that both the initial gain reduction and the rate of gain recovery must be adjusted to make the receiver gain complement as nearly as possible the decay of reverberation with time under particular water conditions.

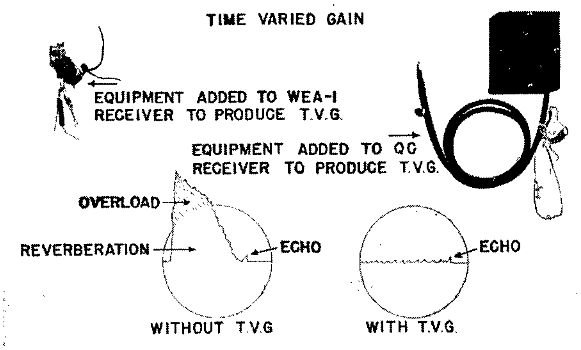


FIGURE 1. Effect of TVG action.

RC Time Constant

If a charged condenser is shunted by a resistance, the voltage across the condenser falls exponentially with time. The time constant, $R \times C$, is defined as the time required for the voltage to fall to $1/e$ times the initial voltage.

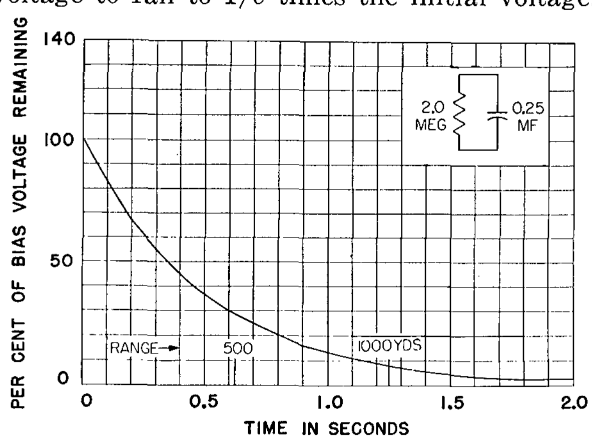


FIGURE 2. TVG action for time constant of 0.5 second.

When such a varying voltage is used as grid bias for an amplifier, its gain can be made to vary with time and hence, range. This is accomplished by the use of remote cutoff pentodes in which gain in decibels is approximately linear with bias voltage.

Figure 2 illustrates the exponential decay of voltage with time in an RC circuit used in a TVG system. Circuit time constants smaller than the 0.5-sec value shown in Figure 2 will provide

more rapid restoration of gain. In general, recovery of gain should be as rapid as possible, consistent with the desired reduction in reverberation.

Manual Gain Control

In the receivers to which TVG has been applied, manual control of gain is accomplished by biasing the amplifier tubes between limits of full gain and cutoff, or near cutoff, by means of adjustable grid or cathode bias. To prevent the amplifier from being wholly nonconducting when the gain-control knob is in the minimum position, a semi-fixed adjustment is usually provided in the listening amplifier.

TVG bias is superimposed upon this manual gain-control bias. If manual control is set too low, and a high initial charging voltage is used in TVG, the receiver amplifier may be biased well beyond cutoff for echoes from targets at relatively small ranges. The optimum relative setting of manual gain and TVG controls varies with the target and water conditions.

Methods of Applying TVG

To reduce the number of manual adjustments, the only control provided is that of initial gain reduction. A compromise time constant, usually between 0.3 and 0.5 sec, is used. There is no provision made for varying it in a particular installation.

Source of TVG Voltage

The negative potential used to charge the condenser depends on the source available in particular installations (such as a polarizing generator), negative voltage sources within the amplifier, or bias voltage obtained by rectifying the transmitter pulse. In all cases, the source voltage must be sufficient to bias the amplifier to, or approximately to, cutoff, when the manual volume control is adjusted to full gain.

Injection of TVG Grid-Control Voltage

The time-varied bias is applied to the amplifier grids by two general methods; it is series-injected into the grid return circuit or placed directly on the grid. In the latter case, the TVG voltage is applied through a resistance large enough to avoid loading the tube input circuit; a fixed condenser is inserted in the grid lead to isolate the d-c bias. Where the TVG voltage is applied to the grid return, the size of the TVG condenser is more than sufficient to maintain the grid return substantially at ground potential at signal frequency. This is the preferable connection since it avoids detuning and cross-modulation effects.

2.3 APPLICATIONS OF TVG

QCL Gear

The method of adding TVG to the 755 QCL receiver is shown in Figure 3. The box which

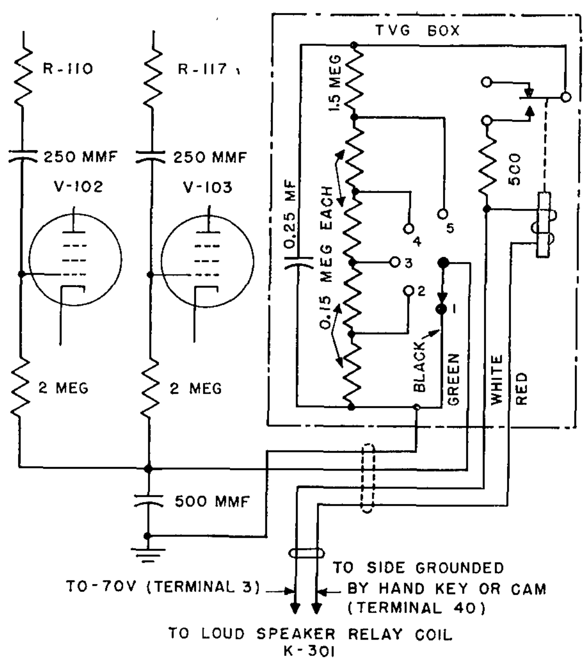


Figure 3. Application of TVG to 755 QCL receiver.

houses the TVG system consists of an RC circuit with a time constant of 0.5 sec, a charging-voltage injection relay, a 500-ohm protective resistor, and a 5-position tap switch for selection of initial gain reduction. The unit is usually mounted on the QC stack, with the TVG control switch accessible to the operator.

The 755 receiver is modified by inserting a 0.00025-μf mica condenser in the grid leads of the first and second i-f amplifier tubes, V-102 and V-103. The TVG control bias is applied to the grids through two 2-megohm resistors whose "low" ends are by-passed to ground through a condenser.

The negative charging voltage source is the polarizing generator for the transducer. The relay for injecting the charging voltage is bridged across the relay which disconnects the loudspeaker during each ping. The taps on the voltage divider provide four initial bias voltages of 20, 15, 10, and 5; tap number 1 eliminates TVG action.

WEA-1 Gear

Figure 4 illustrates how TVG is applied to WEA-1 equipment. The negative charging volt-

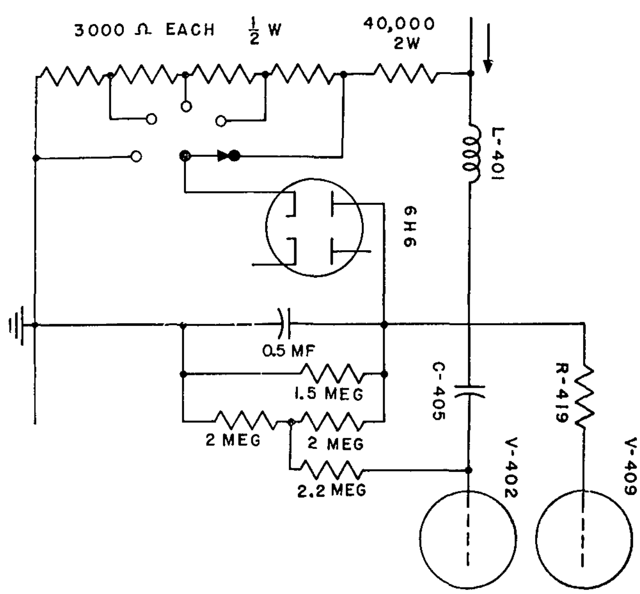


FIGURE 4. Application of TVG to WEA-1 equipment.

age is obtained by rectifying the transmitted pulse. The unused half of a 6H6 tube in the receiver is employed as the rectifier. Four steps of charging voltage are provided as well as an off position.

TVG action is obtained by injecting half of the TVG bias control voltage into the grid return of the final i-f amplifier tube, V-402. This is accomplished by bridging two 2-megohm resistors across the TVG condenser and connecting the grid resistor, R-402, to the common junction.

Adding TVG to WEA-1 equipment slightly refined the gear itself. Since WEA-1 equipment has neither a send-receiver relay nor a speaker cutoff relay, the transmitted ping is accompanied by the same disturbing noise that characterizes the initial reverberation following reception of an echo. To cut off the audio amplifier effectively during each ping, the full voltage of the TVG bias control is applied to the grid return of the first audio stage, V-409.

Other Gear

In RCA QCJ-2 and QCJ-8 equipments, TVG voltage is obtained from the same negative source that provides bias for the manual gain control. The positive end of the TVG voltage-divider is connected back to the negative control point of the manual gain control. A special advantage is gained in this installation since the amount of initial TVG action is a function of gain setting. Thus, TVG suppression of gain cannot be added to manual reduction of gain to hold the receiver at cutoff for appreciable range.

Application of TVG to the Submarine Signal Company 869 QBE receiver is accomplished through blocking action in an amplifier grid circuit. Since remote cutoff tubes are not used in this amplifier, an RC circuit is inserted directly into the grid lead of the first amplifier tube. The jumper which would normally ground the input during each ping is removed and a 5,000-ohm charging resistor is inserted in the input lead. The transmitting signal-voltage pulse thus charges the TVG condenser by grid rectification during each ping. Since the voltage reached by the condenser is, within limits, a function of pulse length, TVG action becomes a function of pulse length. No other adjustment of TVG is provided.

2.4 PERFORMANCE

Experience indicates that with proper adjustment of TVG controls, the primary function of auditory relief can be accomplished without interfering appreciably with the functional

usefulness of the echo-ranging equipment. However, if controls are improperly set, there is the possibility that target echoes may be lost at short ranges since excessive TVG action cuts out the listening amplifier for a short fraction of the listening interval. This possibility of improper adjustment has led to restrictions in the allowable degree of variation; in some cases recovery is so rapid and the reduction in initial gain so small that the primary purpose of TVG is defeated. These limitations have resulted in an imperfect realization, in practice, of the inherent advantages of TVG. However, through the development of RCG, these restrictions have been largely overcome.

While TVG relieves the auditory abuse of the operator, it also clarifies and cleans up the trace obtained on the chemical range recorder. By reducing the level of range reverberation, much of the irrelevant marking on the recorded trace is either eliminated or materially reduced. This greatly simplifies the interpretation of recorder trace patterns.

Reverberation-Controlled Gain

Reverberation-controlled gain [RCG] is a circuit which reduces the output of a sonar receiver during the period of initial reverberation, thereby protecting the operator from a high signal level. Normal sensitivity is restored at a rate determined by the decrease in reverberation. The RCG control circuit was proposed by engineers of the General Electric Company and was developed by HUSL.

2.5 PRINCIPLES OF RCG OPERATION

General Description

The RCG circuit constitutes an improvement over the earlier TVG circuit in that it automatically adjusts the gain as rapidly as is consistent with the prevailing level of reverberation. In TVG, the operator may make an incorrect choice of the initial charging voltage for local water conditions. This can lead to loss of the echo or admission of an uncomfortable blast of initial reverberation. RCG reduces these possibilities and eliminates the need for specific adjustments to correspond to varying conditions.

In RCG operation, immediately following the transmission of the ping, the circuit automatically lowers the gain of the sonar receiver to a point where the loudspeaker level is properly adjusted to the operator's ear. As the initial blast of reverberation dies away, the gain of the receiver automatically rises at a rate sufficient to keep the speaker output level approximately constant. When reverberation has ceased, the receiver gain is that which would be obtained with the existing setting of the receiver gain control.

The action within a single ping interval is irreversible. For example, when the gain has increased part of the way due to decay of reverberation, no amount of subsequent echo signal can cause the gain to be reduced again within the interval. Since the system operates as a sort of unidirectional AVC, compression of echoes, characteristic of ordinary AVC, is prevented.

If no reverberation is received the gain of the receiver reaches substantially the full value,

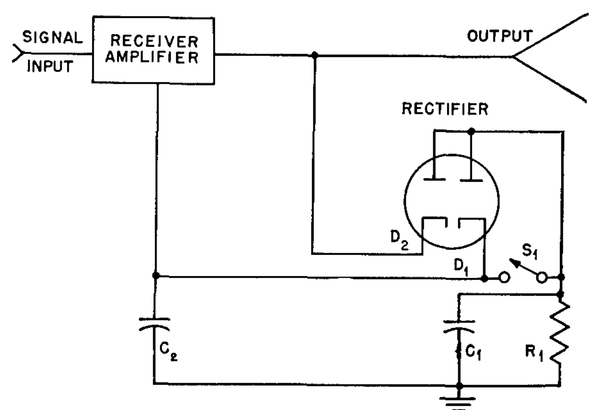


Figure 5. Basic RCG circuit, exterior charging voltage.

corresponding to the sensitivity control setting, in a small fraction of a second following the ping. Thus, the RCG circuit permits the operator to use a high gain setting on the receiver during all echo-ranging operations and almost completely eliminates the need for repeated adjustments of the receiver sensitivity control.

RCG Circuit

The method of RCG control in a typical echo-ranging cycle may be understood by reference

to Figure 5. During the transmission of the pulse, switch S-1 is closed, thus charging condenser C-2 negatively. At the conclusion of the transmitted pulse, S-1 opens, leaving the condenser negatively charged. Returning reverberation causes voltage to appear at the receiver output. This is rectified by diode D-2 and a voltage is developed across its load R-1, C-1. With the RCG circuit properly adjusted, this load voltage is less than that initially applied to C-2. The excess voltage across C-2 will begin to discharge through D-1 and R-1 to ground. As the voltage across C-2 decreases, there is a corresponding increase in the gain of the receiver, in the receiver output, and hence in the voltage built up across R-1, C-1. This process continues as long as the voltage across C-2 is greater than that across the diode load R-1, C-1; i.e., receiver gain increases only so long as reverberation decreases.

However, an increase in input voltage cannot affect receiver gain. An increase in input corresponding to the arrival of an echo produces an actual increase in loudspeaker output. The echo is amplified according to the gain setting of the system at the time it arrived. At the termination of the echo, the speaker signal drops and any other signal is then amplified at the gain setting that existed before the echo arrived.

AVC Characteristics of RCG

During the period of diminishing reverberation, when RCG is raising the gain of the receiver amplifier, the system responds as if the diode D-1 were shorted out; i.e., it is essentially an AVC system that is recovering from a loud signal. Experience has shown that the time constant of the recovery function should be approximately 0.05 sec.

The function of an RCG system is to keep bringing the receiver output back to an approximately constant level following each decrease in receiver input voltage. Consequently, the AVC system formed by shorting diode D-1 must have certain characteristics. For satisfactory operation, it has been found that a 1-db increase in output should require at least a 5-db increase in input. This allows the manual gain control to be run at a relatively higher level without causing receiver overload on initial reverberation. Receiver gain will, therefore, rise to a higher level and weak echoes will be less likely to be missed.

Methods of Charging Control Condenser

Fixed Negative Power Supply. The control condenser C-2 may be charged during the transmitted pulse by direct connection to some negative power supply, as illustrated in Figure 5. The voltage selected should be no higher than necessary to prevent receiver overload on initial reverberation with manual gain control set close to its maximum. Otherwise, there is danger that short-range echoes may be lost in the finite time required for receiver gain to be restored.

Use of Diode. Instead of a fixed negative source for charging C-2, switch S-1 can be connected directly across diode D-1, as in Figure 6.

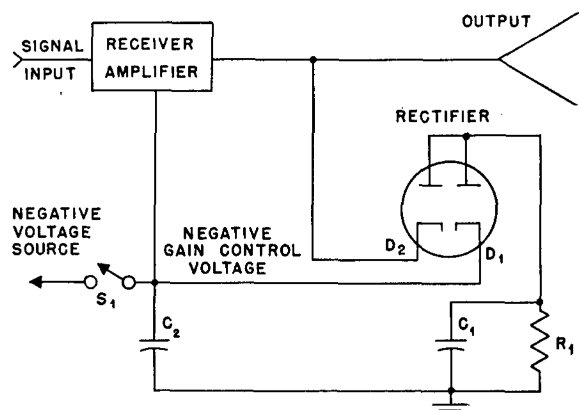


FIGURE 6. Basic RCG circuit, signal charging voltage.

In this case, charging condenser C-2 rises to the same potential as C-1, and the receiver amplifier is actually under AVC during the transmitted pulse. To decrease the gain by a sufficient amount, the input voltage to the receiver must be greater during the transmitted pulse than at any other time in the echo-ranging cycle. Because of leakage from driver to rectifier, this condition exists without special provision in most echo-ranging equipment.

The main advantage of using the diode source to charge the control condenser is that the voltage on C-2 can never be high enough to cut off completely the control tubes of the receiver amplifier. Furthermore, since the signal input to the receiver is strongest during the transmitted

pulse, sufficient voltage will always be applied to C-2 to decrease the gain by the desired amount. In this AVC-type system, the initial charge placed on C-2 is automatically varied according to manual gain control setting. This lessens the probability that short-range echoes will be lost at low manual gain-control settings, as a result of placing excess charging potential on C-2.

Optimum Time Constants

In order to make sure that the AVC system has reached equilibrium in the time allowed by the transmitted pulse, the time constant for charging condenser C-2 must be kept down to about 25 msec. In practice, because of the characteristics of the AVC adopted, the effective time constant will be of the order of 5 msec or less. This is less than the shortest transmitting pulse length used by conventional QC sonar gear.

The rate at which receiver gain is allowed to be restored following the ping is controlled by the time constant R-1, C-2. As a result of considerable experience, this is fixed at approximately 60 msec.

Application of Control Voltage to Amplifier

RCG control voltage is usually applied to the grids of the i-f tubes in the receiver amplifier through a resistor of about 2 megohms. A small condenser is introduced into each grid lead to isolate the d-c voltage. In some installations, it is more convenient to apply the control voltage to the suppressor grids.

Other Considerations

When an echo-ranging receiver (with RCG applied to control grids) is used without recycling over extended periods for listening only, the grids may become increasingly positive as a result of electron emission. This may be overcome by shunting a resistance across condenser C-2 to provide a d-c path to ground, as shown in Figure 7A. However, when reverberation level is constant for any appreciable time, the presence of the shunt resistor allows the negative potential on C-2 to decrease and receiver gain to rise. This undesirable effect can be minimized by making R-2 as large as good practice will permit.

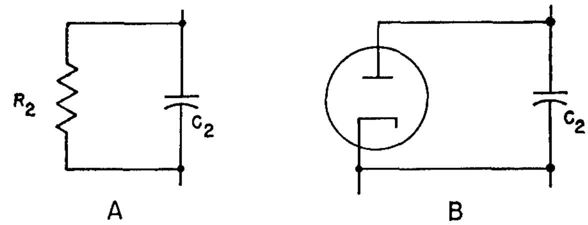


FIGURE 7. Methods of keeping RCG condenser C-2 from going positive during listening.

A slightly more desirable method accomplishes the same result by using a diode across C-2, as shown in Figure 7B. The diode effectively by-passes to ground any positive charge which tries to build up on C-2.

2.6 APPLICATIONS OF RCG

Echo-Ranging Booster

The first semipermanent equipment to employ RCG was the *echo-ranging booster* [ERB]. This unit was designed as an auxiliary to existing sonar equipment and included in addition to RCG, *own-doppler nullifier* [ODN] (see Section 4.2.2), and *reverberation suppression filter* [RSF] (see Section 4.12).

Figure 8A is a partial diagram of Model 1 ERB, showing the RCG and related portions of the circuit. The relay used for RCG also serves to control the ODN functions. For satisfactory ODN operation, this relay must remain closed for approximately 90 msec following each ping. Since the system is held under AVC throughout this period, any echo returning will undergo a certain amount of volume compression. Under some conditions, this action was responsible for loss of target at ranges up to about 100 yd. The use of separate relays for RCG and ODN later remedied this disadvantage.

Figure 8B shows the all-electronic RCG system used in the later version of the ERB. This system charges C-2 by the AVC method but the AVC voltage comes from a separate amplifier

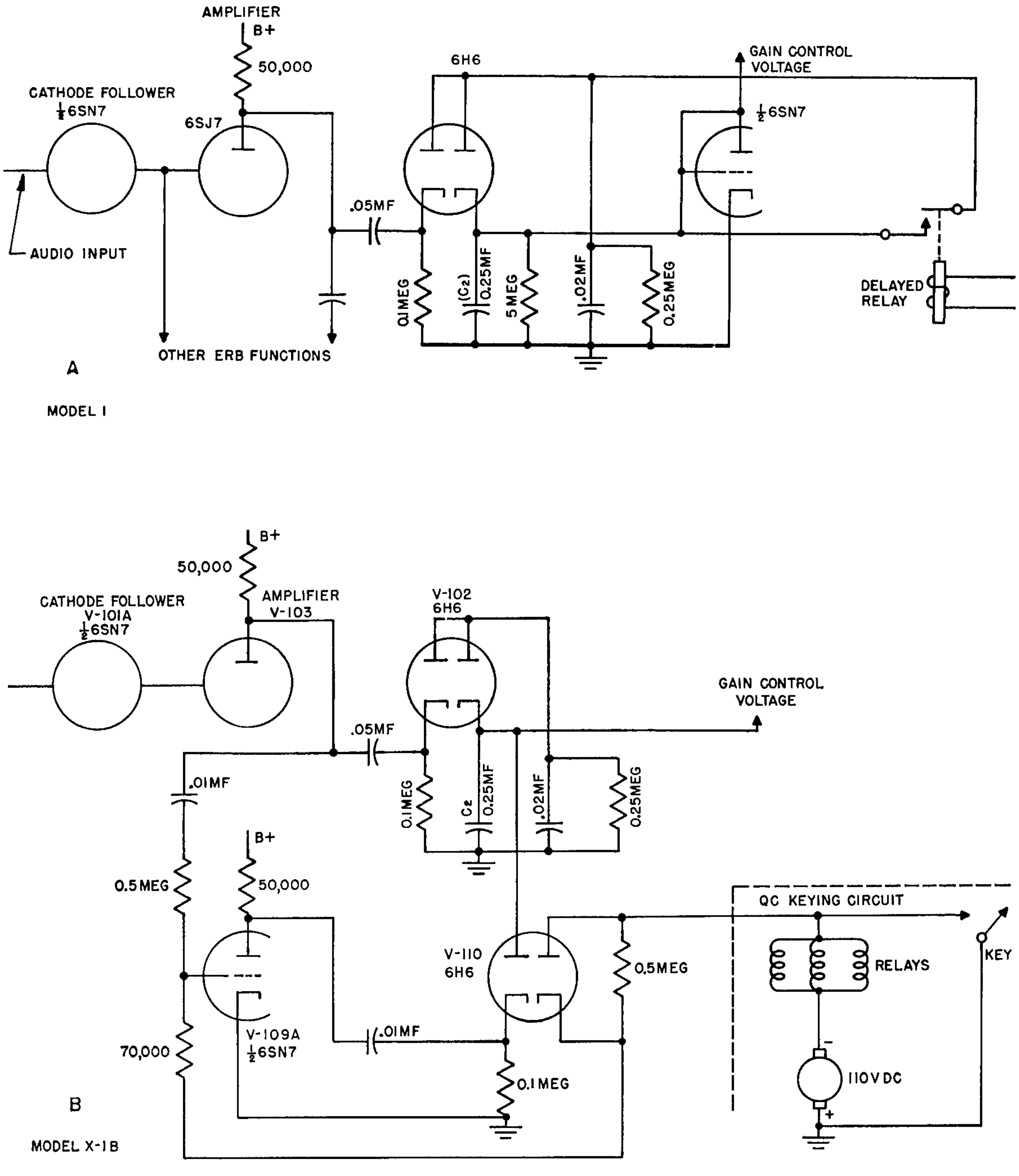


FIGURE 8. RCG portion of ERB circuit.

and rectifier. The grid of this separate amplifier is cut off except during the transmitted pulse and for a very short time thereafter.

The ERB contains the only RCG system that was made up in a form to be installed on equipment already in existence.

SUBMARINE SIGNAL COMPANY MODEL WFA

The essential parts of the RCG system built into the Submarine Signal Company Model WFA sonar receiver are shown in Figure 9.

This circuit has been considered the best modification of the basic RCG circuit. Since the RCG control voltage is applied to the suppressor

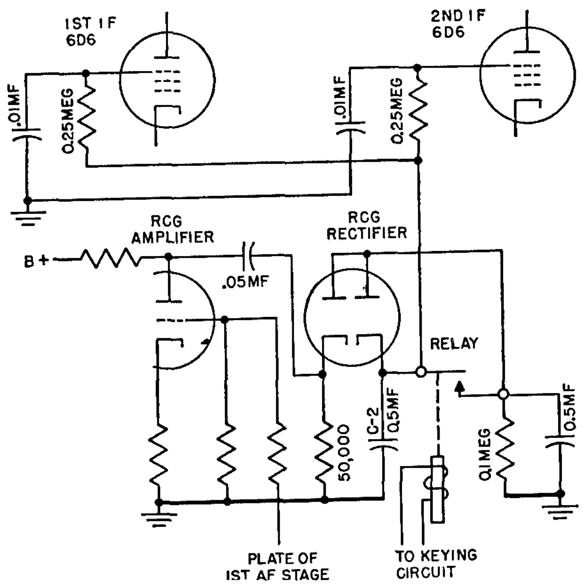


FIGURE 9. RCG system on Submarine Signal Company WFA equipment.

grids of the i-f amplifiers, it is not necessary to use a leak resistor or diode across C-2. Furthermore, the suppressor grids have a comparatively high gain-controlled sensitivity which introduces very satisfactory AVC characteristics. Finally, initial charging of the condenser is accomplished by shorting out the delay diode during transmission rather than by use of a fixed negative voltage. As explained above, this reduces the possibility of losing targets at close range.

OTHER GEAR

RCG has also been adapted to other gear, such as the RCA Model QGB, the Western Electric Model QJB, the Sangamo Model XQHA, as well as the sum and difference bearing deviation indicator.

2.7 PERFORMANCE

RCG provides substantially the optimum variation of sonar receiver gain required to overcome the adverse effects of reverberation during the listening period following pulse transmission. Its use effectively eliminates the necessity for the sonar operator to readjust receiver gain during search or during the progress of an antisubmarine attack. As a result, this method of gain control has been widely adopted by the U. S. Navy for standard sonar equipment.

Automatic Gain Control (British)

The automatic gain control [AGC] is an automatic volume control circuit used with British Asdic equipment to reduce receiver output during reception of initial and subsequent reverberation. A comparison of RCG and AGC was made by His Majesty's A/S Engineering Establishment at Fairlie, Ayreshire, and their report is summarized here.

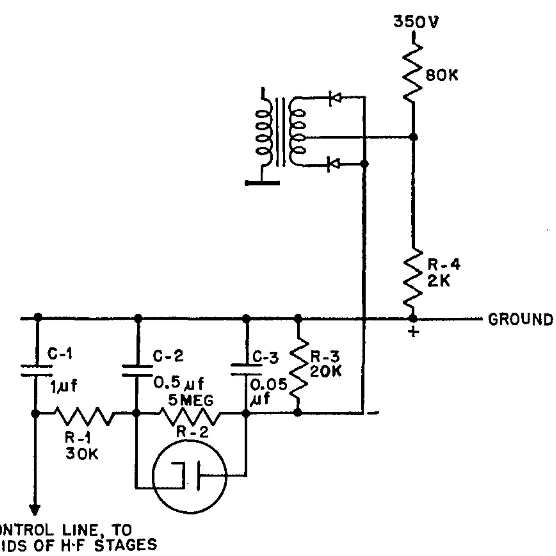


FIGURE 10. Time-delay circuit used in AGC.

2.8 PRINCIPLES OF AGC OPERATION

GENERAL DESCRIPTION

The British AGC system provides a method of varying the gain of the sonar receiver following transmission of the ping so that the background of reverberation is held to an almost constant level. To this extent, it is similar to the RCG system. However, the AGC has an

advantage when used in shallow-water echo ranging. Because of a time-delay circuit introduced into the gain-control network, it automatically discriminates between slow rises in input due to increased reverberation and sudden rises due to echoes.

Time-Delay Circuit

The required time delay is achieved by charging the final condenser, C-1, through a 5-megohm resistance, R-2, as shown in Figure 10. The effective time constant (RC) in this case is approximately 500 msec, which is adequate to cover the duration of the longest echo.

In order to reproduce in their original intensities echoes following each other in quick succession, a diode is used to quickly remove the bias arising from an echo. If no rectifier were used for discharge, the decay would be very slow. The diode is connected across the high resistance with such a polarity that it conducts when the voltage on C-3 is less negative than the voltage on C-2. The time delay introduced in the AGC network is not constant but depends greatly on the strength of the suddenly applied signal. The ratio of initial charging voltage to final voltage is almost directly proportional to the strength of the input signal; this fact is responsible for decreased time delay at high signal strengths.

2.9 COMPARISON OF AGC AND RCG

When the reverberations fall continuously after transmission, both systems will exert similar controls on the receiver gain, and the reverberation output will be held to an almost constant level. When an echo arrives, RCG will reproduce it at proportional intensity for its complete duration while AGC will give a "clipped" echo. On the cessation of the echo, the bias on RCG will have the value that existed before the echo arrived, whereas the AGC system will require an interval to restore itself to the gain that existed prior to the arrival of the echo. In conditions where the reverberation level rises at any time during reception, the AGC system will counteract this by increasing the bias on the control line and so reduce the background to a previously existing level. The RCG system, on the other hand, will be unable to adjust itself to the increased reverberation level and consequently the rise in reverberation will be manifested by an increase in receiver output.

After study of the circuit characteristics in various laboratory performance tests, a field comparison was made of the two systems. The locations of these tests was a shallow channel. The oscillograms shown in Figure 11, reproduced from the British report, show the incoming signal and the two types of control produced by AGC and RCG.

Figure 11A shows the incoming signal with the receiver uncontrolled. The output of an RCG-controlled receiver and corresponding bias produced across its control line are pictured in Figure 11B. The AGC output and its bias for the same incoming signal are shown in Figures 11C, 11D, and 11E, respectively. Comparison of the oscillograms for the two systems reveals the improved compression of reverberation with AGC for these conditions, as well as the clipping effects produced by AGC on the echoes.

2.10 PERFORMANCE

The RCG system is superior to the AGC in deep water where the reverberation level falls continuously; with RCG there is no opportunity for the clipping effect to obscure the indication of pulse duration. However, in shallow water, where the reverberation level may exhibit a rise during some point in reception, the RCG system may prove less satisfactory because of its inability to distinguish between slow rises in input level caused by increased reverberation and sudden rises in input level produced by echoes.

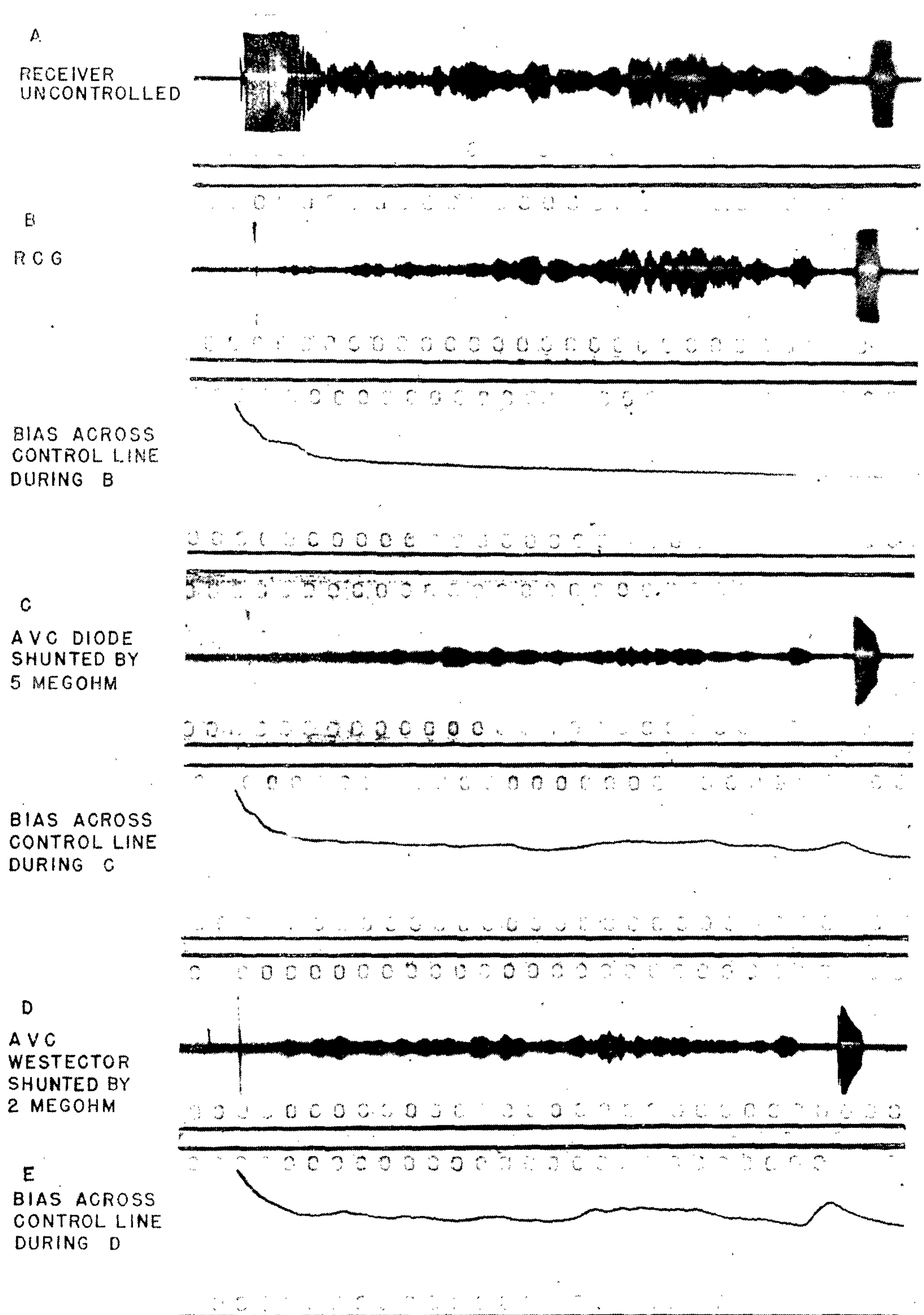


FIGURE 11. Comparison of RCG and AGC action in shallow water. Reverberations and echo on 15 kc/s.

Chapter 3

AUTOMATIC PROJECTOR TRAINING SYSTEMS

3.1 INTRODUCTION

THIS CHAPTER CONTAINS a description of three systems proposed for automatic projector training: *automatic target training* [ATT], *maintenance of true bearing* [MTB] and *electronic automatic search* [EAS]. For each of these, the development is briefly discussed, its operation described, and performance characteristics evaluated.

Automatic target training equipment was developed to improve the accuracy of bearing determinations made by the sonar operator and to relieve him of the constant strain of maintaining contact with the target. ATT trains the projector in the direction of the target by utilizing the output of the *bearing deviation indicator* [BDI]; by means of a range gate, ATT responds only to an echo arriving from the proper target. ATT was never officially put into production because it required excessive monitoring on the part of the sonar operator, without being more effective than a combination of the sonar gear with a BDI attachment.

Maintenance of true bearing is a training system developed to overcome the difficulties resulting from rapid changes in target during an attack. It is used with sonar systems to provide a means for automatically maintaining the projector on any desired bearing with respect to truth north, regardless of the relative bearing with respect to the ship. The MTB training system uses a differential action to combine the rotation of the projector shaft within the ship and the rotation of the ship in space; it translates this resulting indication into automatic maintenance of the desired projector bearing and provides a means for superimposing changes in true bearing as desired by the handwheel operator. Several hundred of these systems were installed in ships by the Navy. Performance tests indicated a good static accuracy of follow-up of the entire system with as rapid operation as that of the original training control. Its use was recommended particularly for smaller vessels because of their general instability and yawing tendencies.

Electronic automatic search is a system developed to operate a ship's sonar gear automatically during the search period in accordance with a previously determined pattern in ping-listen-train sequence. It consists of electronic circuits which, with a motor, furnish electrical control signals to the transmitter and training unit of a sonar system having selsyn training. Performance tests indicated that EAS was effective in producing uniform successive keying intervals and a small accumulated error of train. The system was never adopted for use by the Navy because it was superseded by a new automatic search plan.

Automatic Target Training

Automatic target training [ATT], a modification of standard sonar equipment, was devised for the purpose of maintaining the sonar projector automatically and continuously trained on the target, once contact has been made. To accomplish this, the ATT unit is supplied with (1) intelligence concerning the target bearing from the bearing deviation indicator [BDI] and (2) information regarding the target range from a tactical range recorder. The ATT chassis utilizes the BDI input to effect training of the projector in azimuth to follow an echo, and the range recorder input to restrict the training to follow an echo of a particular range. In this manner a projector and its ATT unit are said to be automatically focused both in azimuth and in range. The automatic target training program was conducted by HUSL.

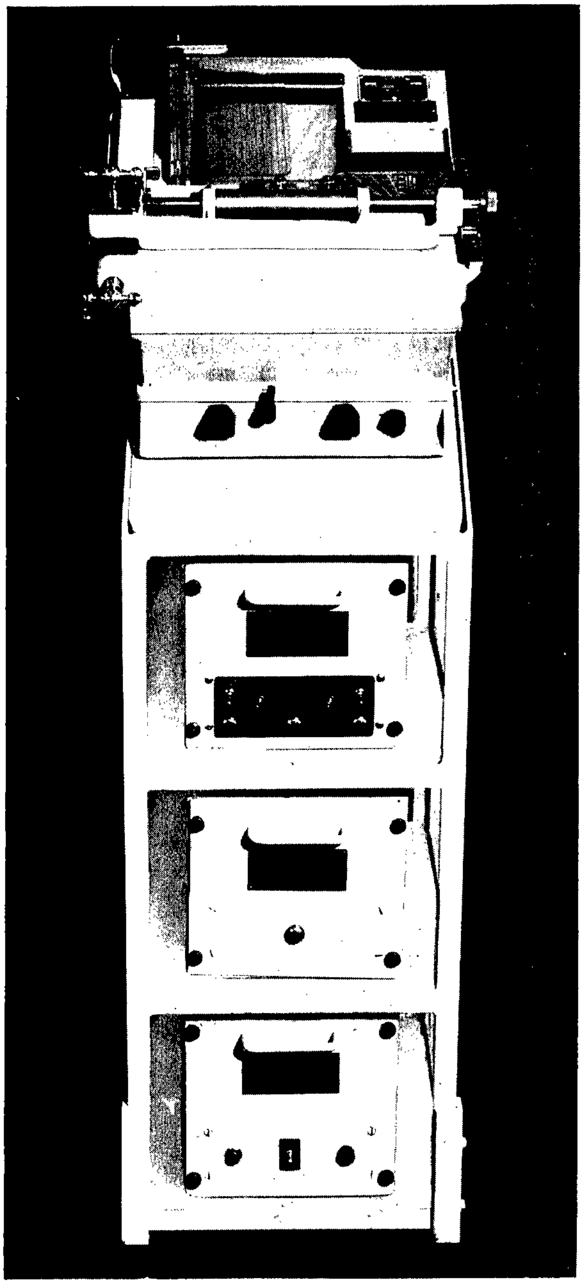


FIGURE 1. Echo-ranging conversion unit for automatic target training.

3.2 GENERAL DESCRIPTION

The function of the ATT is to train the projector of underwater sound ranging equipment continuously and automatically in the direction of a submarine target, once contact has been made. The ATT system receives right-left information electrically from the BDI; these voltages give right or left sense to a motor-control circuit which trains the projector accordingly. The equipment is made to respond only to an echo arriving from the proper target by means of a range gate. The range-gate control is derived from an attachment to the tactical range recorder which restricts the function of automatic training to the time interval corresponding to the range of a particular target. A pipping circuit is also provided to produce on the BDI oscilloscope screen a traverse of pips which appear as two horizontal lines bracketing the echo.

INFORMATION FROM THE BDI

The first system using BDI information to effect corrective training of a projector in azimuth is shown in the block diagram of Figure 2. The directional output of the BDI (a model antedating the X-1 BDI) from the 7- and 10-kc channels is fed into amplifiers and then into comparison and sum rectifiers. The amplified outputs of the rectifiers operate relays which control illumination of colored lamps and an indicating meter giving right and left readings. This circuit, which is the forerunner of all the later circuits developed for azimuth training, was modified several times. The final model, which was tested on shipboard, employed as input the information from the 7- and 10-kc amplifiers of the X-3 BDI.

RANGE GATE

In order to restrict the operation of the training motor to the interval during which an echo of a particular range reaches the projector, and so make the training circuit unresponsive to reverberation and to other echoes, a range-gating circuit was devised. The first range gate, which was mechanical, had the disadvantage of requiring the constant attention of an additional operator. An automatic gate was then developed by modifying the tactical range recorder. An additional set of contacts was installed and arranged to be engaged by the spring contactor as it reached the range position at which the contacts were located. The final automatic range gate provided an overrunning clutch, using a continuous stainless steel belt running over

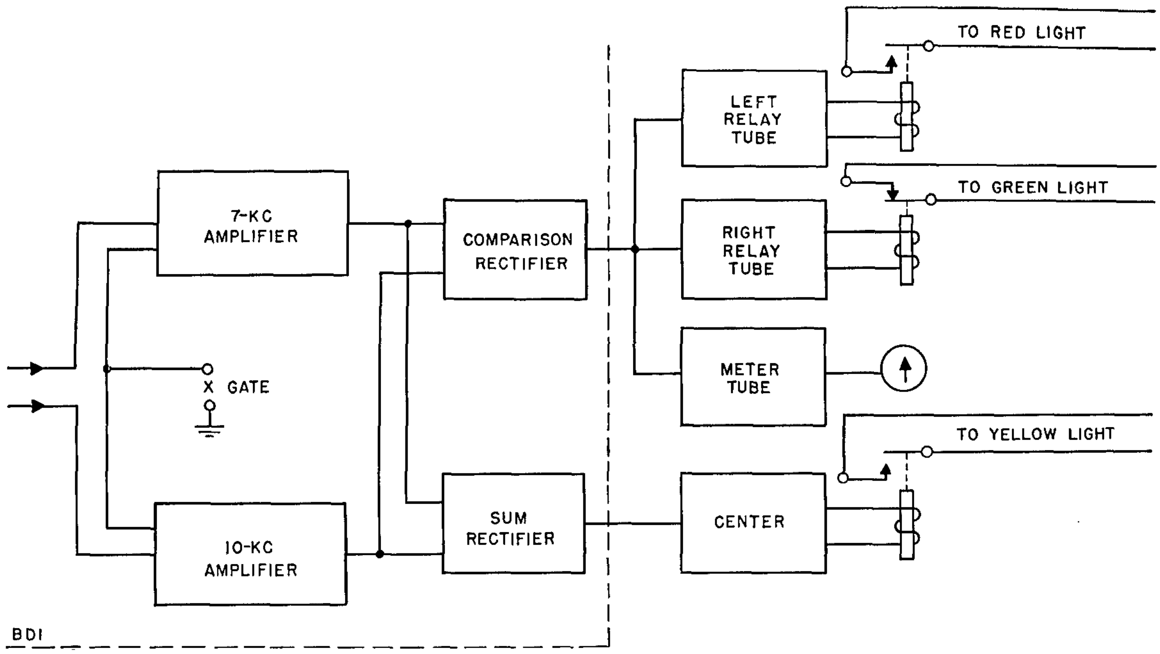


FIGURE 2. Block diagram of ATT chassis Model 1.

spools at the back of the recorder. The contact assembly was connected to the flyback control, the handle for which appears on the front of the recorder. This method, shown in Figure 3, proved entirely adequate and was used in all subsequent installations.

The electronic circuit which has only one relay (the gating relay) is shown in Figure 4, and was used as shown or with slight modifications in all the later ATT chassis. It is extremely sensitive and on several occasions gave evidence of being able to train on signals which had so little contrast with the prevailing noise background as to be indistinguishable on the recorder trace.

In order to make it possible for the sound operator at the echo-ranging stack to determine the position of the gate relative to the echo, it was found desirable to provide marking lines or "pips" on the CRO of the BDI to indicate the start and end of the gate interval. Figure 5 shows circuit producing desired pips.

ATT Motor Control Systems

The input to an ATT chassis consists of two components: (1) the intelligence from the BDI regarding the bearing of the projector relative to the target, and (2) information from the range gate relative to the echo returned by the target. Correspondingly, the output of the ATT chassis is also composed of two channels: (1) a d-c voltage of the proper polarity and duration to produce the corrective azimuth training of the projector, and (2) similarly a d-c voltage to move the range gate so that the echo lies centrally within the gate. This section describes the methods by which the ATT output is applied to motors which effect the azimuth and the range-gate focusing.

Vacuum Tube Motor Drive. The purpose of the vacuum tube motor drive is to provide means of controlling both the speed and the direction of rotation of a small two-phase motor from a low-amplitude d-c input. The direction of rotation must depend on the polarity of the input and the speed must depend on the amplitude of this input. For the requirements of ATT, this method was found inferior to some developed subsequently.

Thyratron Drive. The purpose of the thyratron drive is to provide a means of controlling the rotation of a small two-phase motor from a small difference in d-c potential. More specifically, the direction of rotation is to depend upon

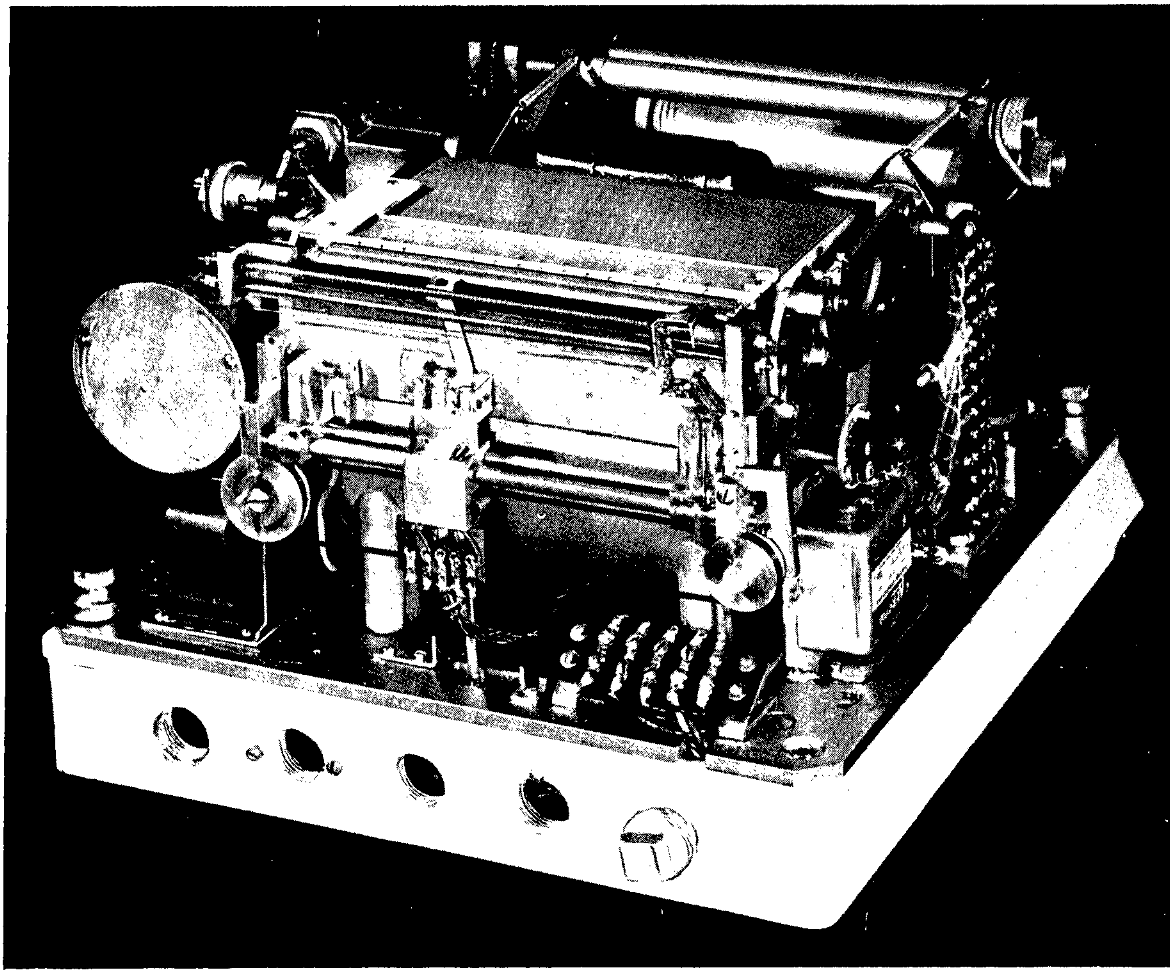


FIGURE 3. Sangamo recorder modified for ATT, steel belt drive.

the polarity of the d-c, the time of rotation is to depend upon the duration of the applied d-c above a small minimum value, and the motor torque is to be constant rather than proportional to the input. Figure 6 is a schematic diagram of of the two-tube thyratron drive, the first successful thyratron circuit developed. The four-tube thyratron drive circuit (Figure 7), is essentially a modification of the one shown in Figure 6, which had been developed for a specific installation in which a higher efficiency was required.

METHODS OF APPLYING ATT OUTPUT TO PROJECTOR TRAINING

The output of an ATT chassis may be coupled to the projector training mechanism in three ways, depending upon the kind of training control used: (1) thyratron-controlled training, (2) selsyn training systems, and (3) direct servo drive training.

Thyratron-Controlled Training. One of the earliest methods of training a projector employed a handwheel generator to energize a thyratron drive connected to the training mechanism motor. In one case, the directional output of the ATT chassis is used to drive a low-power, two-phase motor geared to the handwheel (see Figure 8A). The second scheme, shown in Figure 8B, employs a rectifying and filtering system to convert the a-c output of the ATT chassis to d-c which is then fed into the thyratron drive. This latter method, however, has the disadvantage that all the modifying circuits must be off ground to avoid interference with the grounding of the thyratron control

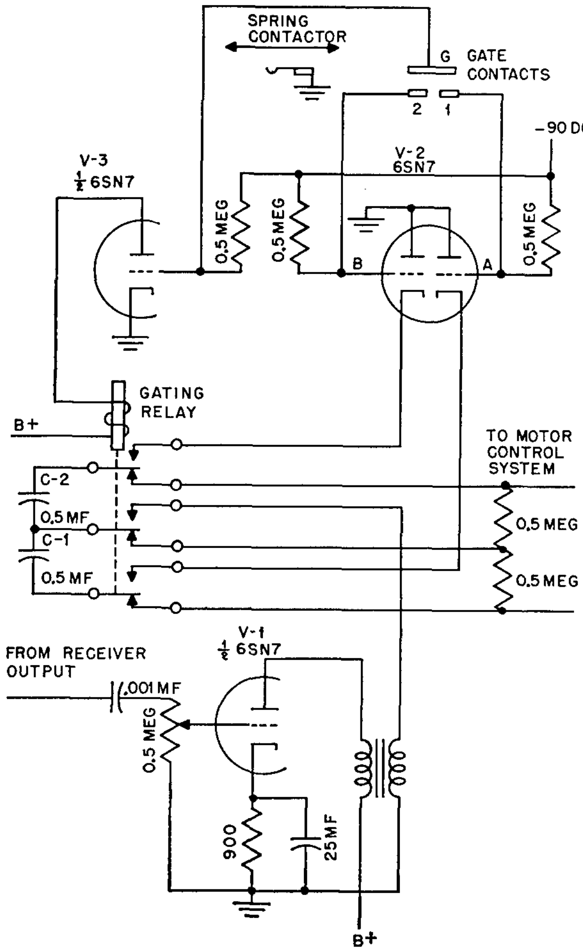


FIGURE 4. Schematic diagram of electronic range gate system.

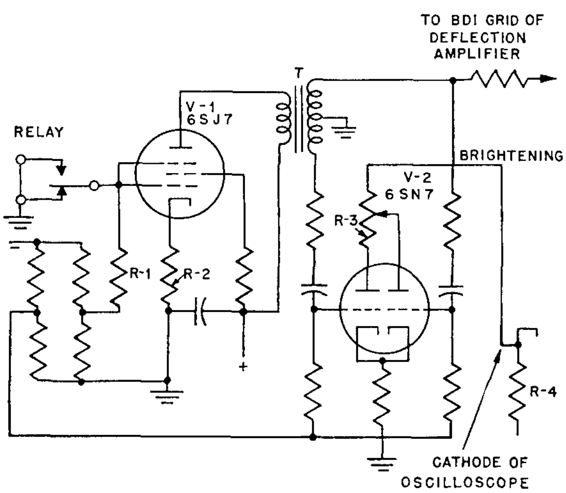


FIGURE 5. Oscilloscope marking circuit.

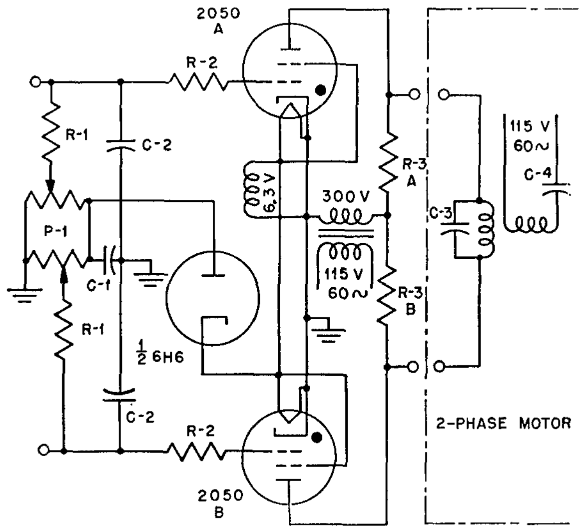


FIGURE 6. Schematic diagram of two-thyratron motor drive.

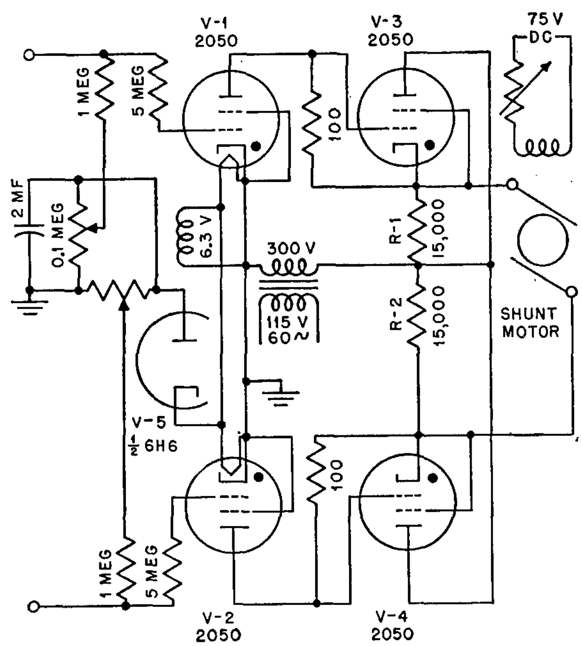


FIGURE 7. Schematic diagram of four-thyratron drive of d-c motor.

input. Neither of the two schemes was put into actual use.

Selsyn Training System. Figure 9 is a block diagram of the selsyn system of training control. To apply the ATT output, a differential selsyn with the proper phase-correcting condensers is inserted between the generator selsyn

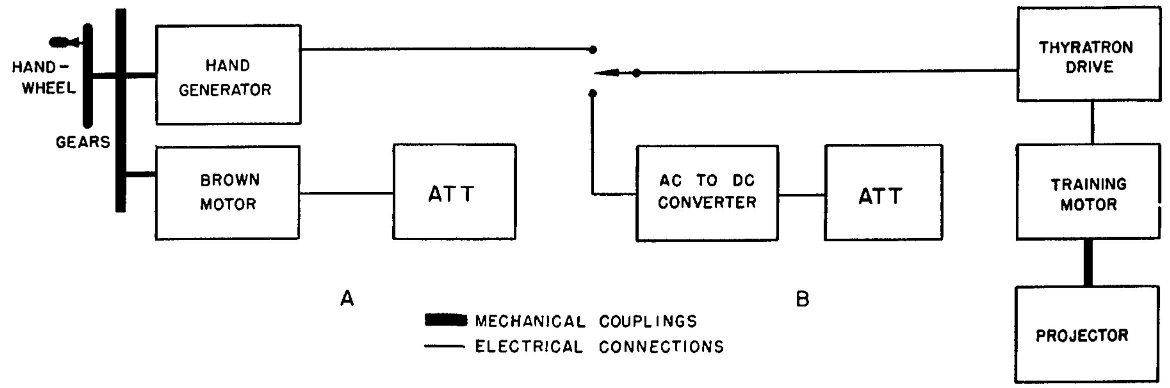


FIGURE 8. Block diagram of thyratron-controlled training. Two-phase low-power motor manufactured by Brown Division of Minneapolis-Honeywell Company.

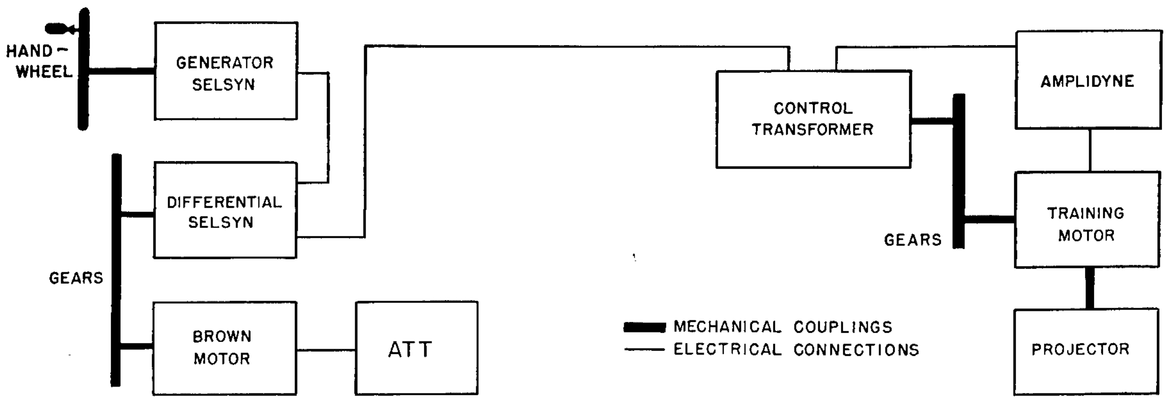


FIGURE 9. Block diagram of selsyn training system.

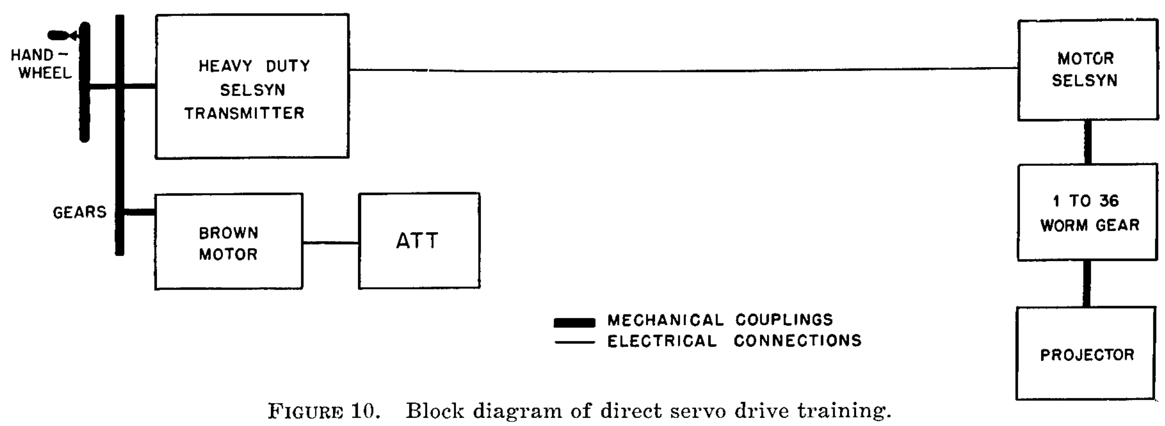


FIGURE 10. Block diagram of direct servo drive training.

and the control transformer. The output of the ATT chassis is then fed into a two-phase motor which is geared to the differential selsyn. This method of training control has proved adequate in several ship installations.

Servo Drive Training. Only one application of direct servo drive training was made (see Figure 10). The motor driven by the ATT output is geared directly to the handwheel of a heavy-duty selsyn transmitter. The output of this transmitter is sufficient to operate the motor selsyn which, in turn, trains the projector

mechanically coupled to it through a worm gear. In operating the selsyn transmitter manually, the extra load of turning the motor is appreciable and the addition of an overrunning clutch is recommended.

3.3 TECHNICAL DETAILS OF FINAL MODEL

Circuit Principles

The ATT system involves the following units:

1. ATT chassis. The ATT chassis contains the electrical circuits which perform the functions of training the projector and actuating the range-gate mechanism.
2. Bearing deviation indicator. The ATT system receives its right-left information electrically from Model X-3 BDI, which gives a continuous indication as to whether reflected signals are being received from directions to the right or to the left of the bearing to which the sound projector is pointed.
3. Tactical range recorder. The recorder employed in the ATT system is equipped with an auxiliary contact block called a range gate, which may be set to any position along the recorder range scale. Its effect is to make the ATT system responsive only to echoes arriving from the range for which the gate is set. The position of the gate can be set manually to begin with, but once contact has been established with the target, a small electric motor, mounted on the recorder, automatically makes the gate follow the changing range of the echo. An additional feature of this equipment is that the length of the transmitting signal is approximately proportional to the range at which the fly-back is set when the recorder is used to key the sound equipment.
4. Automatic training-control motor. A small electric motor is added to the control panel of the sound stack and geared directly to the hand training wheel. The motor serves to rotate the handwheel in the proper direction to train the sound projector toward the target when ATT is used. This training-control motor does not offer serious resistance to hand training.

With minor modifications, the circuit shown in Figure 11 was the final one used on shipboard. Balance stability was found to exist at the output of the 7- and 10-kc amplifiers, and this circuit was designed to utilize information obtained from these points and translate it into a form applicable to the thyratron motor control. By means of the gating method used, the direction of training conforms fairly accurately to the BDI information. This circuit also has the advantage that once the gain controls are set, no additional centering adjustment is necessary.

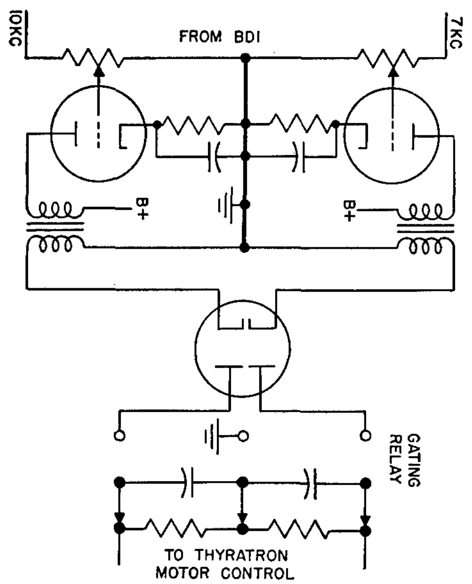


FIGURE 11. Comparison circuit utilizing 7- and 10-kc channels of X-3 BDI.

A further modification, not installed on shipboard, was designed to make use of the intelligence derived from the X-4 "stabilized" BDI.

Circuit Analysis

The block diagram and schematic diagram of the ATT system are shown in Figures 12 and 13, respectively.

Motor Control Circuits. Thyratrons V-9 and V-10 (type 2050) constitute the training motor control circuit used to operate the small two-phase motor which turns the manual training wheel; thyratrons V-6 and V-7 form an identical control circuit to operate a similar motor which drives the gate contact along the range scale of the recorder. The operation of these

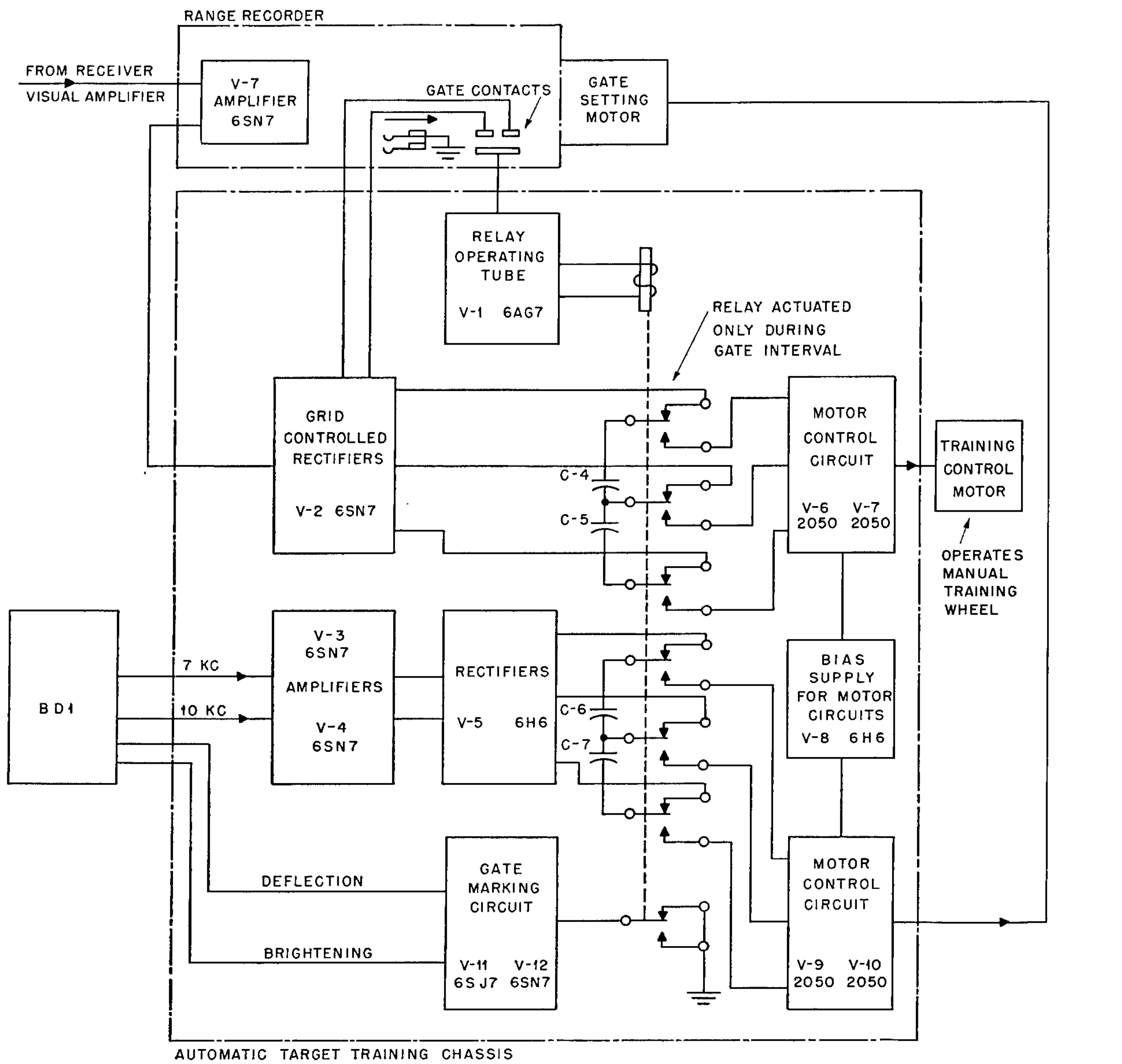
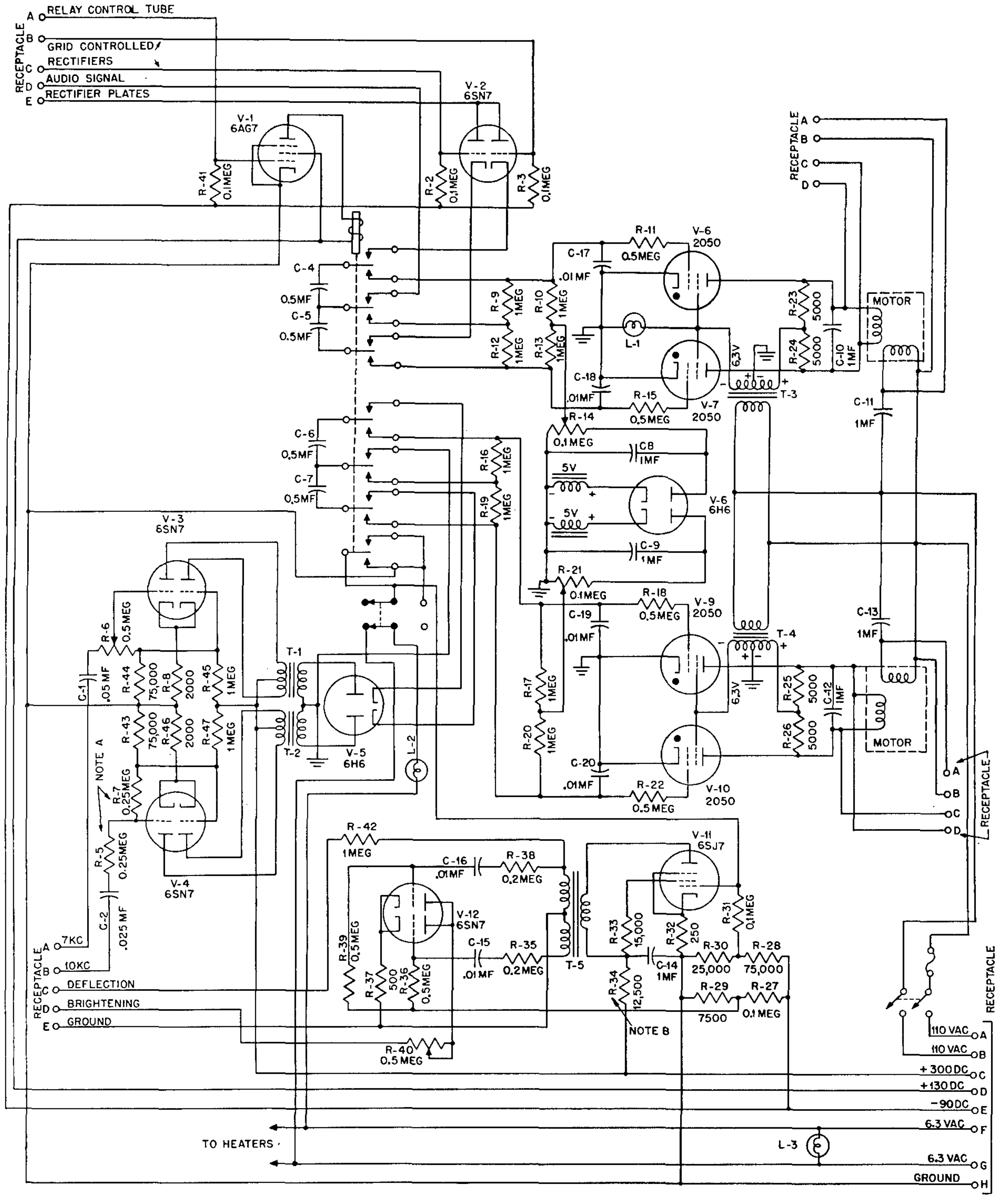


FIGURE 12. Block diagram of ATT chassis.

motor control units is of the on-off type; i.e., the circuits deliver to their respective motors either full power or no power at all. The control signal to each motor circuit takes the form of a d-c voltage which is established between the control grids of its pair of thyratrons. When this d-c voltage exceeds approximately 1 v, the tube whose grid is positive ignites and a 60-c a-c voltage is impressed upon one winding of the associated motor. This voltage is either in phase or exactly out of phase with the line voltage, depending on which thyratron is ignited. One winding of the motor is connected to the a-c line through a 90-degree phase-shifting condenser and, therefore, the direction of rotation of the motor depends upon which thyratron is ignited in the control circuit. Each section of the double diode V-8 acts as a half-wave rectifier to convert voltage from a filament winding into a negative d-c voltage which is used to bias the control grids of both the motor-control-circuit tubes. The magnitudes of the control grid biases are



NOTE. A - TO BE ADJUSTED FOR PROPER LEVEL
NOTE B - TO BE ADJUSTED FOR 250 V
NOTE C - DO NOT CONNECT THIS POINT TO TERMINAL H
IF CHASSIS IS OTHERWISE GROUNDED
IF USED WITHOUT ERB, GROUND TERMINAL H

FIGURE 13. Schematic diagram of ATT chassis.

adjusted by potentiometers R-14 and R-21. The bias voltages are set to a value sufficient to prevent the thyratrons from igniting when no input signal is supplied to the chassis.

Automatic Azimuth Training Circuit. The 7- and 10-kc signals from the BDI are amplified by the push-pull stages V-3 and V-4, respectively, and are rectified by the diode elements of V-5 so as to charge C-6 and C-7, respectively. It will be noted that the charging circuit is complete only when the relay is actuated. At all other times, C-6 and C-7 are connected in series across the control grid circuit of the motor control tubes V-9 and V-10. The charging circuit is so arranged that C-6 and C-7 have opposing polarity, and the polarity of the net voltage between the control grids of V-9 and V-10 depends on which of the BDI signals, the 7- or the 10-kc, had greater amplitude during the period when C-6 and C-7 were receiving their charges. The entire circuit, consisting of the 7- and 10-kc amplifiers V-3 and V-4, the rectifier V-5, and the training-motor driving tubes V-9 and V-10, therefore, serves to drive the manual training wheel in the proper direction, as indicated by the BDI right-left signals, to point the projector toward the target.

Automatic Range Gate Circuit. The motor control tubes V-6 and V-7 are controlled by the net voltage existing across C-4 and C-5, which, in turn, are charged from the grid-controlled rectifiers contained in V-2. The a-c signal which is applied to these rectifiers is obtained from the visual amplifier system of the sound receiver by way of an amplifier located in the recorder. Although V-2 is a double triode, its plate and grids are connected as though the tube were to be used as a pair of diode rectifiers. Normally, the grids are supplied with a 90-v negative potential through resistors R-2 and R-3 and no rectification takes place. However, when the traveling contact finger of the recorder crosses the gate contact block, first one grid of V-2 and then the other is grounded and rectification occurs.

At the same time, the automatic training relay is actuated. The result of this entire performance is that C-4 receives a charge proportional to the intensity of signal delivered by the sound receiver during the first half of the gate interval, while C-5 receives a charge proportional to the intensity of the receiver output during the second half of the gate interval. When the relay ceases to be actuated, following the gate interval, C-4 and C-5 are connected in opposite polarity between the grids of the motor control tubes V-6 and V-7. The final result is that the gate contact on the recorder is moved in the direction of decreasing range if the stronger signal is received during the first half of the gate interval, and in the direction of increasing range if the second signal half is the stronger. This system enables the gate automatically to follow an echo in range as soon as manual adjustment of the initial gate has been made.

The automatic training-relay coil is energized by plate current through the relay control tube V-1. Ordinarily, 90 v negative is impressed on the control grids of V-1 through resistor R-41, but when the traveling contact finger of the recorder engages the long gate contact, this bias is removed and the relay is actuated for the duration of the gate interval. As explained above, the comparison rectifier circuits of V-2 and V-5 can charge their associated condensers only while the relay is closed. It is this feature which makes the ATT system respond only to echoes arriving from a given range interval.

Marking Circuit. Tubes V-11 and V-12 form a marking circuit which indicates the beginning and end of the gate interval by creating horizontal lines on the cathode-ray tube screen of the BDI. The control grid of V-11 is normally maintained at ground potential through either side of a single-pole double-throw contact of the automatic training relay, but when the swinging contact moves from one position to the other, as at the beginning or end of the gate interval, the control grid of V-11 momentarily receives a large negative bias through R-31. The sudden change in plate current of V-11 causes large voltage surges to occur in the secondary of T-5. These are delivered to the horizontal deflection amplifier of the BDI to produce the desired marks on the cathode-ray screen. Tube V-12 consists of two triode elements which are connected across the cathode resistor of the BDI cathode-ray tube. The voltage surges from the secondary of T-5, which serve to produce the horizontal marks on the BDI cathode-ray screen,

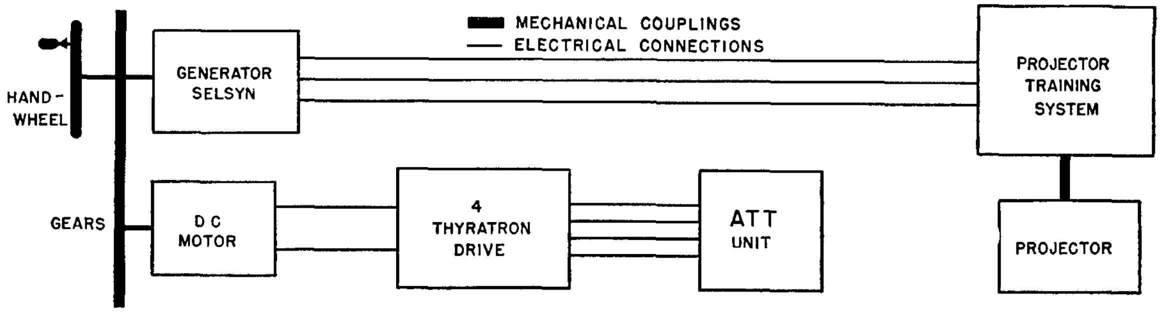


FIGURE 14. Selsyn system.

are delivered to the grids of V-12. As a result, V-12 draws increased current, which decreases the cathode bias of the cathode-ray tube and brightens the cathode-ray spot.

3.4 PERFORMANCE

Tests were performed on a typical installation (see Figure 14), to check the performance of the ATT gate. Ranges indicated on one recorder were tabulated with the corresponding positions of the range gate automatically indicated on another recorder, the stylus of which was servo driven from the ATT resistor strip. A number of runs were made, using surface ships at rest for targets on a day when echo-ranging conditions were excellent.

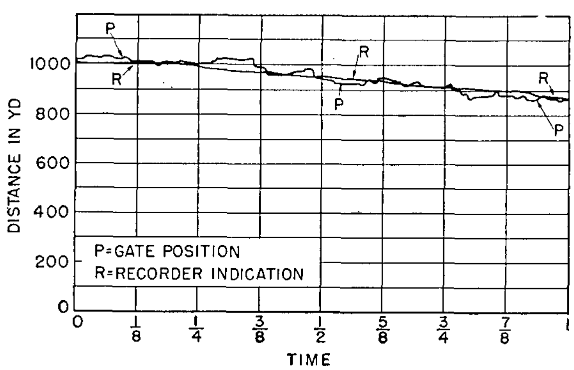


FIGURE 15. Performance of automatic range gate, Run No. 1.

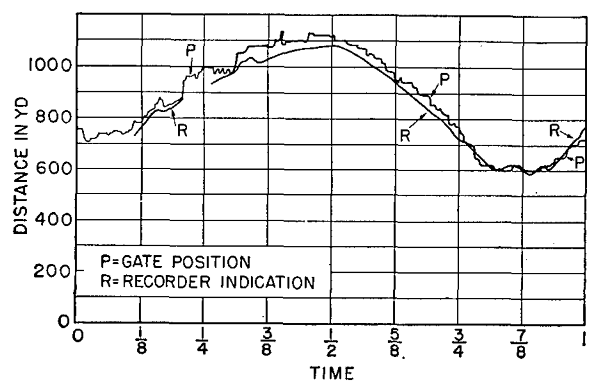


FIGURE 16. Performance of automatic range gate, Run No. 2.

Typical results of these runs are shown by Figures 15 and 16. The graph of Figure 15 is a plot of the data of Run No. 1, taken at slow speed with a slowly closing range. The mean deviation was found to be 17 yd. The graph of Figure 16 is indicative of the results obtained during Run No. 2, when the range was changed fairly rapidly between 700 and 1,100 yd. The mean deviation in this case is somewhat larger than for Run No. 1. The accuracy of these graphs is not absolutely known since the mechanism operating the sound recorder was subject to an inherent error of ± 10 yd. Additional data and curves are given in reference 2.

3.5 CRITIQUE OF FINAL MODEL

The outstanding difficulty present in the ATT system is the requirement of excessive monitoring by the sonar operator. This is particularly true in the presence of wakes and false targets. Most of the equipment problems were solved, although relay contacts continued to be a source of trouble.

Conclusions drawn from tests have been prepared in reports [1] and are summarized as follows:

The ATT functions as designed and will follow even weak echoes as long as there are no interfering echo sources. In some cases, it even discriminates to a remarkable extent between submarine echoes and interfering echoes.

The performance of average sound school operators on manual BDI is approximately equivalent to their performance on ATT. Under difficult conditions, the average operator's ability to hold contact is not increased by the use of ATT. Inasmuch as ATT requires the same degree of operating skill, it is not felt that it is as good as ordinary manually operated sonar with bearing deviation attachment.

In view of the additional complexity and maintenance problems without added advantage, it is not recommended that ATT be adopted as a standard attachment. However, it is recommended that development be continued toward the end of applying fully boosted right-left indications to the follower system.

3.6 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

In the time since active work on the ATT was suspended, consideration has been given to various methods by which the performance of ATT could be significantly improved. An all-electronic ATT system has been proposed which would improve the construction and operating characteristics of the electronic circuits. This system is described fully in a HUSL completion report on ATT.[1]

Briefly, the features of this proposed system are as follows:

1. Elimination of all relay contacts, and elimination of the tactical range recorder as a source of range information.
2. Elimination of manual monitoring through increased accuracy, training proportional to bearing deviations, utilization of doppler enhancement to increase target echo sensitivity and to minimize response to wake echoes.

The all-electronic ATT system, with improvements in the servo mechanism, has not been tested experimentally but it would appear to offer the most promising lines upon which to attack the ATT problem.

Maintenance of True Bearing

Maintenance of true bearing [MTB], developed by the New London Laboratory of CUDWR, designates an automatic projector training system developed for use with sonar equipment for surface vessels. The MTB provides a means for automatically maintaining the orientation of the projector on any desired true bearing as established by the sonar operator through a handwheel, even though the vessel changes course. In its final form, the MTB consists essentially of a synchro differential generator for combining ship and projector bearing information; a synchro control transformer, driven by the differential generator and governing the operation of the projector training motor; and a synchro generator-motor system for obtaining true bearing indication. Although it was originally designed for installation in a new type of console, the equipment was also made available in the form of conversion kits for use with both amplidyne- and thyratron-controlled types of gear already in service. Several hundred projector training mechanisms were equipped with MTB by the Navy and were found satisfactory.

FIGURE 17. Model 1 MTB experimental unit.

3.7 GENERAL DESCRIPTION

Maintenance of true bearing is a system intended for addition to previous sonar equipment to make the projector maintain automatically any desired bearing with respect to true north, regardless of the relative bearing with respect to the ship. MTB incorporates three features: (1) a differential action which registers and combines the rotation of the projector shaft within the ship and the rotation of the ship in space; (2) translation through a suitable control mechanism of the resulting indication of the desired projector bearing into automatic maintenance of this bearing; and (3) provision of means for superimposing changes in true bearing as desired by the handwheel operator.

In the operation of final models of MTB, indication of true bearing is furnished in the form of synchro signal voltages from the ship's gyro compass repeater system. If these voltages are delivered to the stator of a differential generator, the rotor reports its position with respect to true north. Since the rotor of the differential generator is also subject to mechanical changes in position through operation of an associated handwheel, the output voltages of the differential generator will be the resultant of (1) the position of the gyro compass repeater system, reporting the ship's true bearing, and (2) the manually established position of the differential rotor reflecting desired true bearing of the projector.

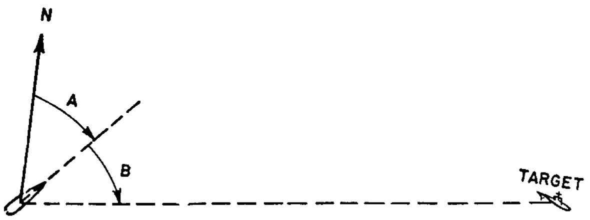


FIGURE 18. Target bearing angles.

These features make it easier for the operator to keep a projector trained on the target. On a sonar gear having MTB, the operator need only adjust the training handwheel to correct for gradual changes in true bearing of the target (angle $A + B$ of Figure 18) instead of having to keep up with rapid changes in relative bearing (angle B) as his ship yaws and maneuvers.

3.8 DEVELOPMENT OF SUCCESSIVE MODELS

Model 1

In the first design the ship's gyro repeater, a step-by-step d-c motor, fed the information of the ship's bearing (angle A of Figure 18) into a planetary differential gear box. The instantaneous relative bearing of the projector (angle B of Figure 18) was fed to the differential gear box by a 5F synchro motor. This synchro motor was actuated by a synchro generator geared to the projector (see Figure 19). The differential gear automatically added the two angles fed into it and caused a shaft carrying the body of a potentiometer to take up a position corresponding to the angle $A + B$—the instantaneous true bearing.

This potentiometer was a part of the power supply circuit for the projector training motor. Its body was a plastic plate carrying two segmented brass rings connected by a network of resistors to form a center-tapped potentiometer. (A later model is shown schematically in Figure 22.) The wiper-arm center tap was on a separate shaft controlled by a handwheel.

Assume the operator set this handwheel at a desired true bearing angle $(A + B)$ which was the same as the existing true bearing angle at which the differential gear had placed the body of the potentiometer. The wiper-arm then fell at the zero voltage position and the training motor was not actuated. However, if the ship changed its course the same relative projector bearing would correspond to a different true bearing and so the differential gear would turn the potentiometer body to a new position. This would leave the wiper arm no longer at the zero point and so the potentiometer would feed voltage to the training motor. This caused the latter to rotate the projector until the exciting voltage disappeared; i.e., until the original desired true bearing was regained. The system thus automatically maintained the projector on any true bearing selected by the handwheel operator.

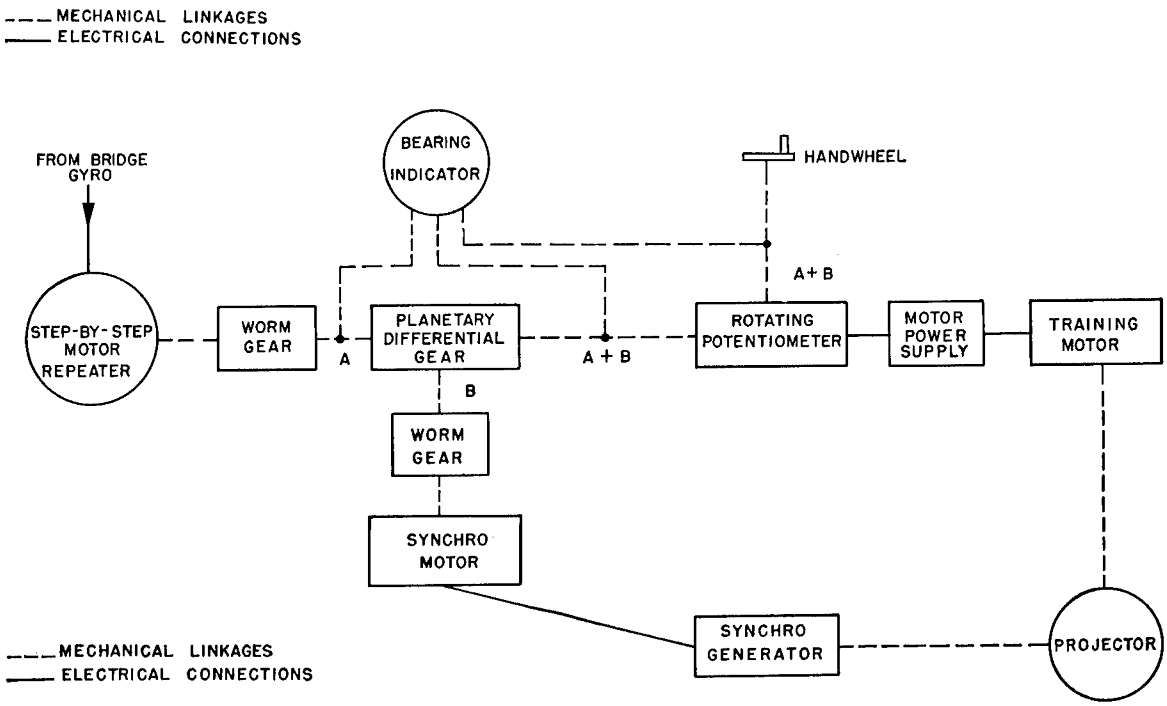


FIGURE 19. Block diagram of Model 1 MTB system.

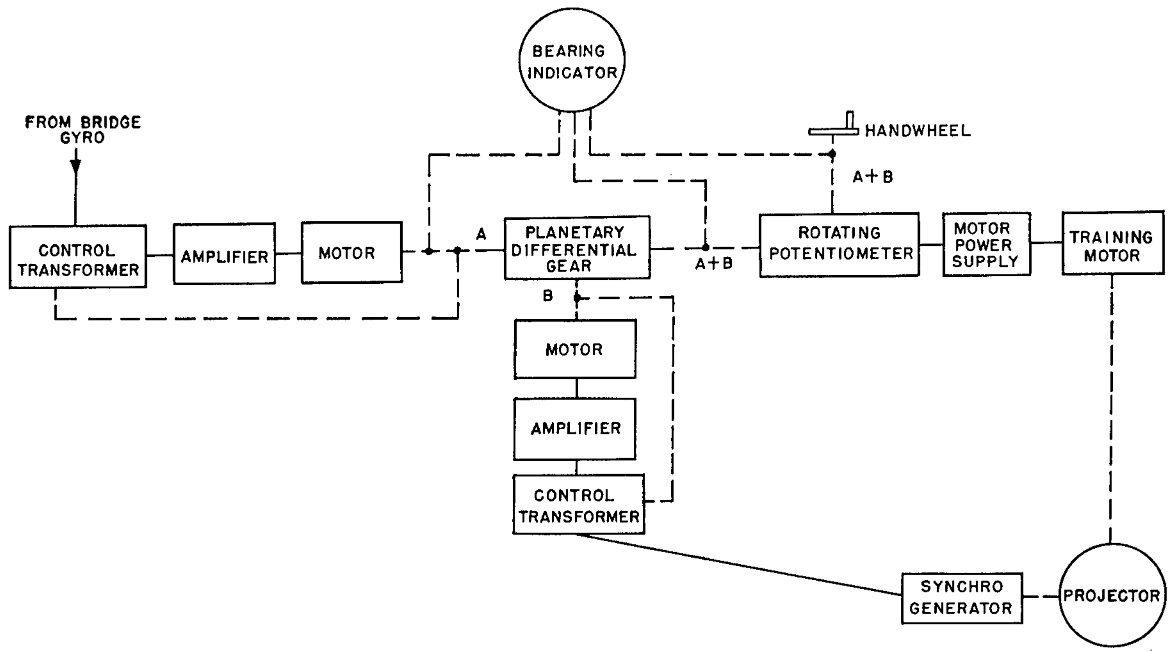


FIGURE 20. Block diagram of Model 3 MTB system.

The bearing indicator dials were actuated by gear trains from the gyro repeater, from the differential gear output, and from the handwheel to show ship's bearing, projector true bearing, and desired projector true bearing, respectively.

Since the mechanical construction of the differential gear was rather heavy and utilized

sleeve-type bearings, it was necessary to operate its two driving motors at relatively high speeds into worm reductions. Another disadvantage of the unit was that it required considerable "running-in" before proper operation could be obtained.

Models 2 and 3

The next model was built to smaller scale, and was of lighter construction, utilizing ball bearings wherever possible. The worm gears were eliminated and the differential gear was driven by two 5F synchro motors rotating at the same speed as the projector shaft. However, friction in the gears still demanded too much torque from the synchros. Model 2 also included a rotating optical system intended to provide a concentric range indication. This was subsequently abandoned.

In Model 3 both synchro motors were replaced by servo systems to provide more power for operating the differential gear (see Figure 20). Each of these consisted of a *control transformer* [CT] feeding a small two-phase Brown Instrument Company motor through a single-stage vacuum-tube amplifier circuit. After sea tests the Model 3 unit was installed in the Mark I modified QC rack.

Models 4A and 4B

In Model 4A the mechanical construction of the potentiometer was simplified by combining the two segmented rings into one and displacing the wiper arm contacts 180 degrees from each other.

Shortly thereafter a new system, here called Model 4B, was devised wherein the planetary differential gear was replaced by a *differential synchro generator* [DG].

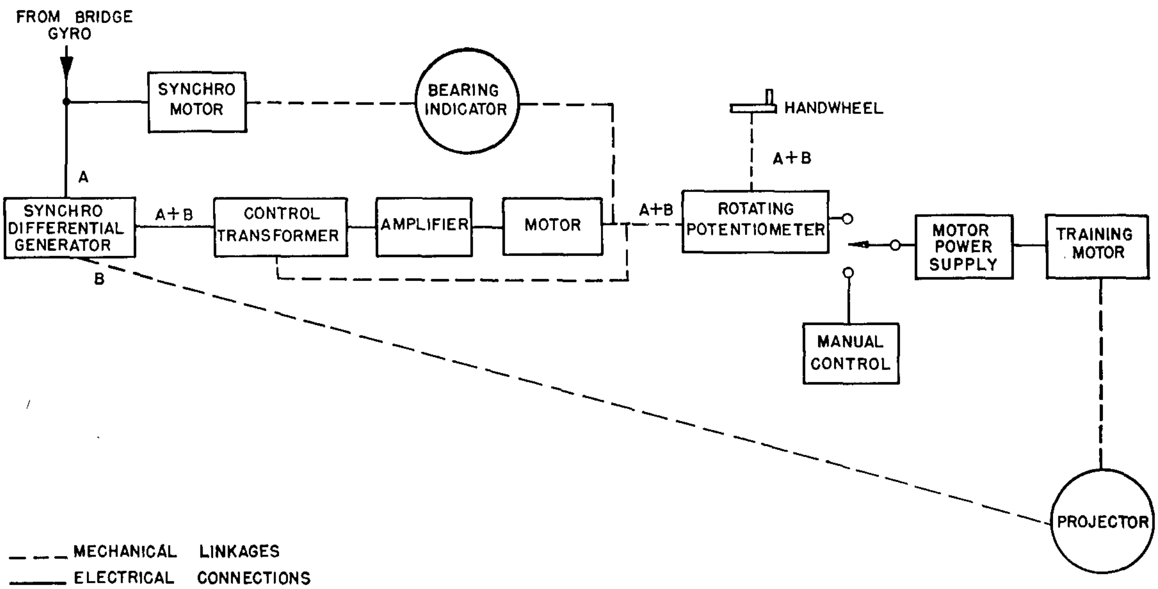


FIGURE 21. Block diagram of Model 4B MTB system.

The stator of this machine received the ship's bearing signal from the gyro repeater lines while the rotor was geared to the projector shaft (Figures 21, 22, and 23). The synchro performed the necessary addition and provided an output signal corresponding to the projector true bearing. One of the previous servos was used to rotate the potentiometer body in accordance with this signal. A separate synchro motor repeated the ship's heading to the bearing indicator in this model. Provision was made for switching back to manual control if the ship's gyro system ever failed. This type of

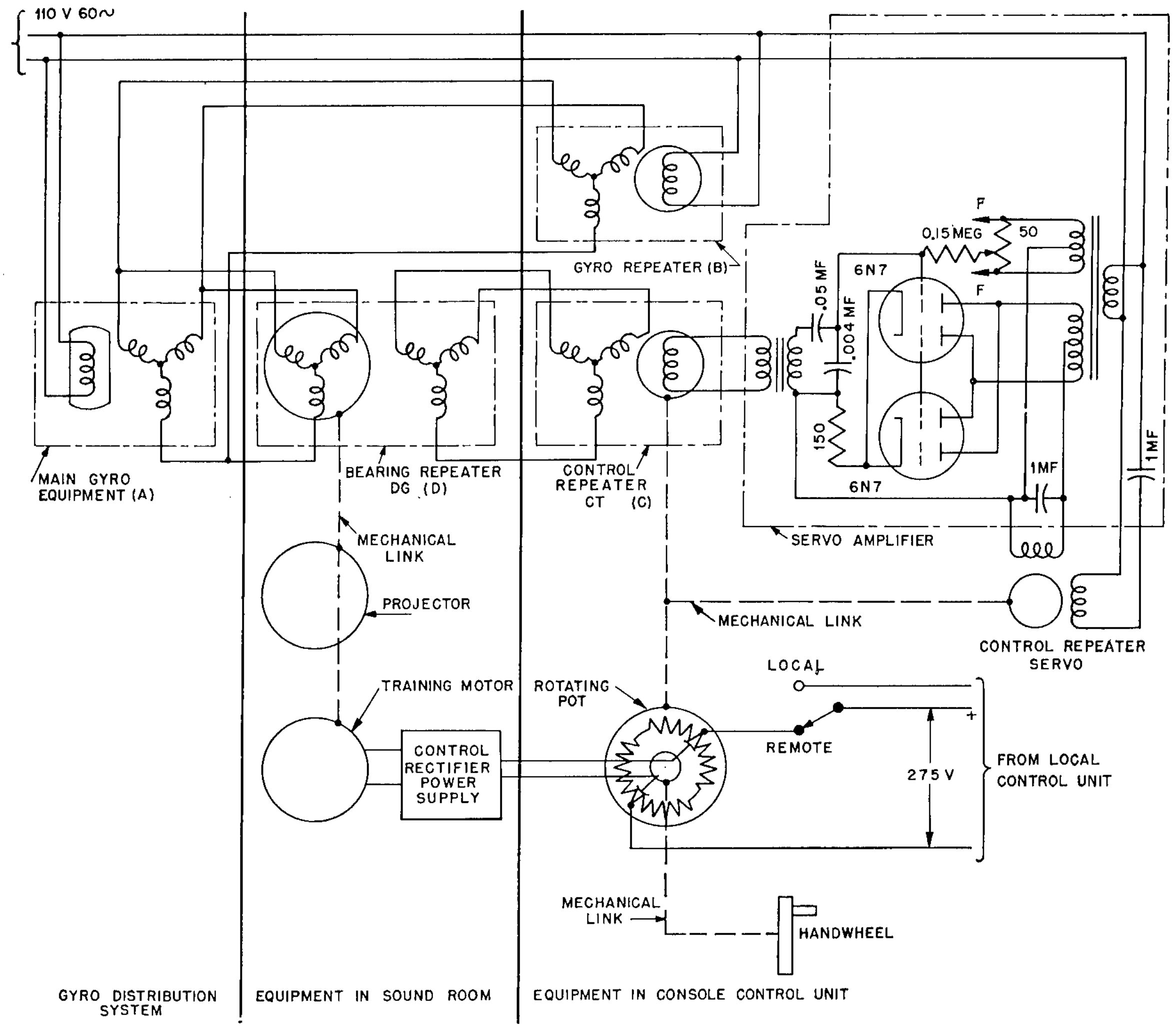


FIGURE 22. Schematic wiring diagram of Model 4B MTB system.

unit was installed in the Mark II modified QC sonar rack.

MODELS 5A AND 5B

The next improvement was to replace the special rotating potentiometer by a commercial control transformer (Figure 24). The transformer stator received the existing projector true bearing signal from the DG synchro as before. The transformer rotor was adjusted by the operator's handwheel to the desired true bearing. If this orientation differed from that of the stator signal an error voltage resulted which was applied to the training motor through an amplifier, with the proper polarity to bring the projector into the desired true bearing.

In Model 5A the bearing indicator received the projector true bearing from a synchro motor actuated by the differential generator. In an emergency, reversion to manual control of relative projector bearing was possible by driving the DG stator from a 115- to 78-v transformer instead of from the ship's gyro system.

A variation of the above, Model 5B, was to interchange the roles of the DG rotor and the CT rotor, the former now being controlled by the handwheel and the latter geared to the projector (Figure 25). With this arrangement the two signals received by the differential gen-

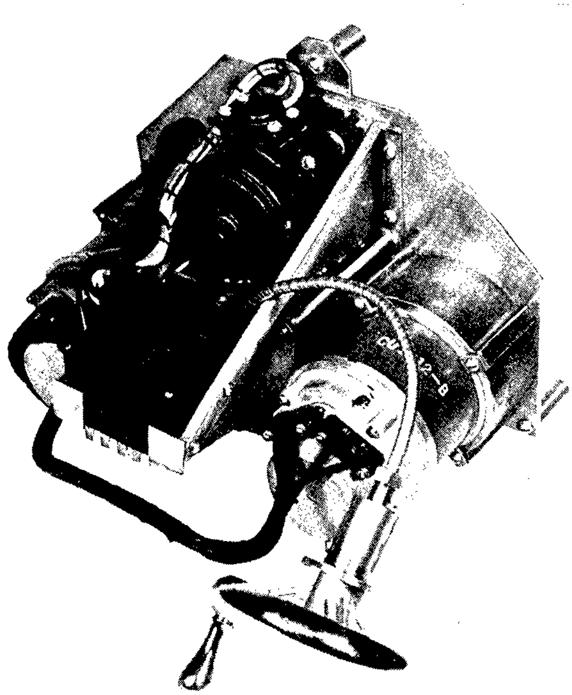


FIGURE 23. Remote control unit of Model 4B MTB system.

erator were the ship's bearing (angle A) and the desired projector true bearing angle $(A + B)$. The differential generator was connected so as to subtract these, producing a signal corresponding to angle B, the necessary projector relative bearing. Any deviation between this direction and the existing projector relative bearing, reported by the CT rotor, produced a CT output voltage. This voltage when amplified, operated the training motor to correct the error.

As it had been found that complete separation of the indication system from the training system led to smoother operation, a separate synchro generator geared to the projector was used in the final design to provide projector bearing indication. Figures 26 and 27 show part of the Model 5 type of equipment.

3.8.1 Conversion Kits

The above equipment was originally developed for inclusion in the new console type of

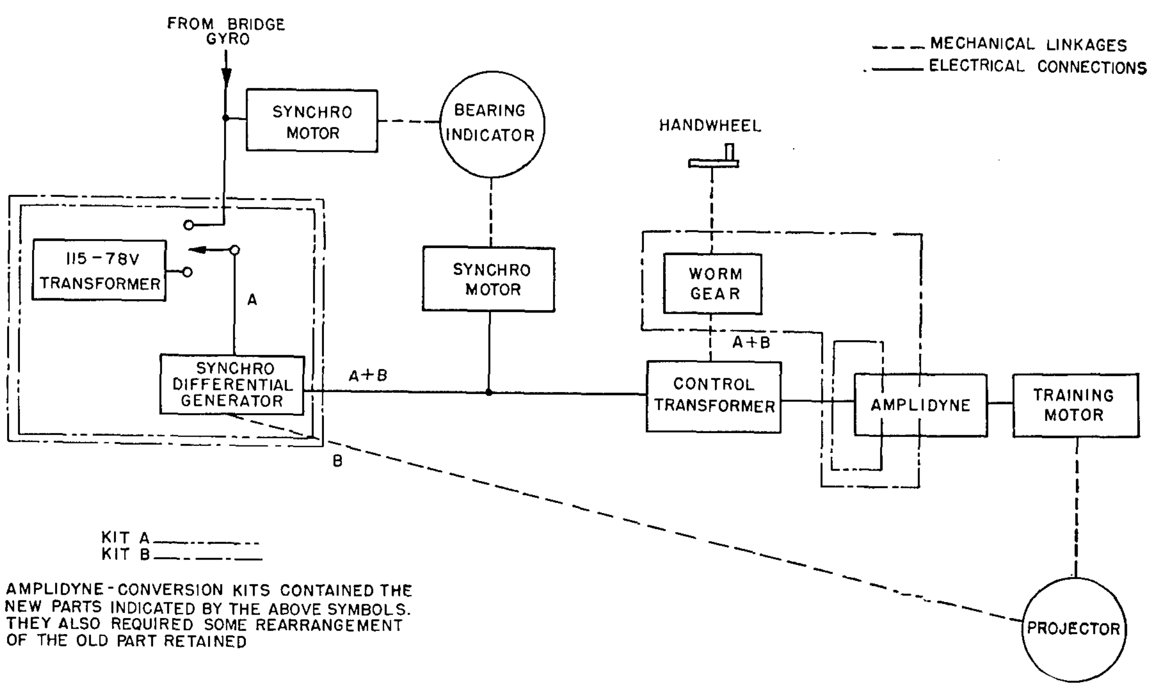


FIGURE 24. Block diagram of Model 5A MTB system.

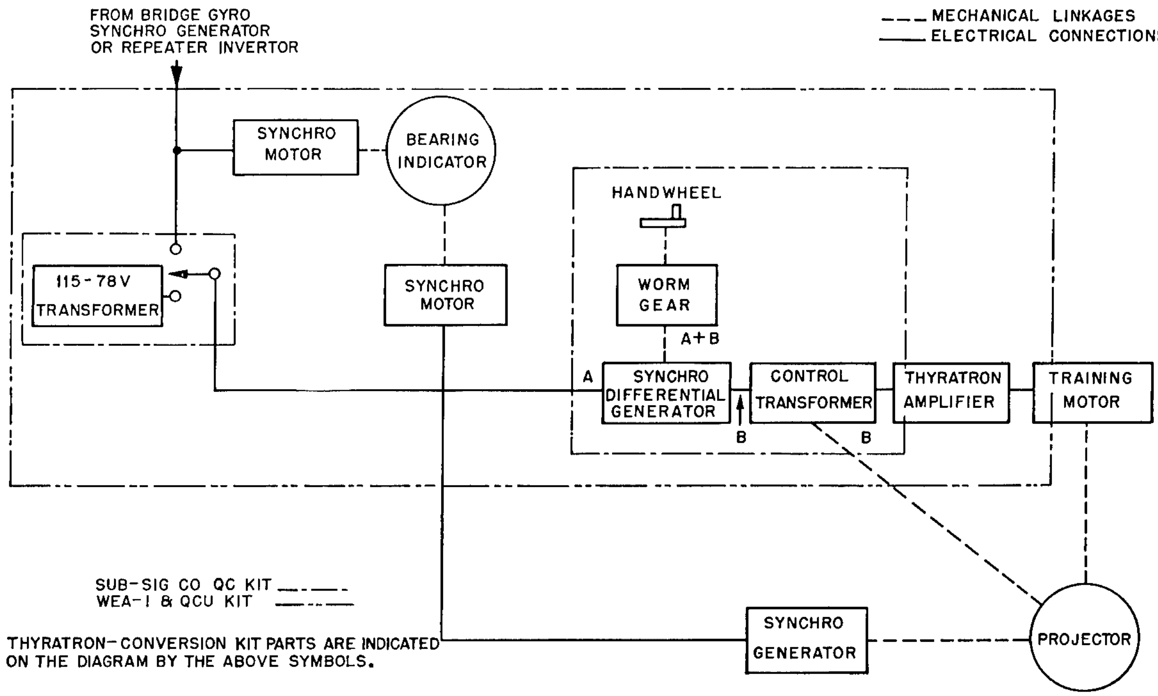


FIGURE 25. Block diagram of Model 5B system.

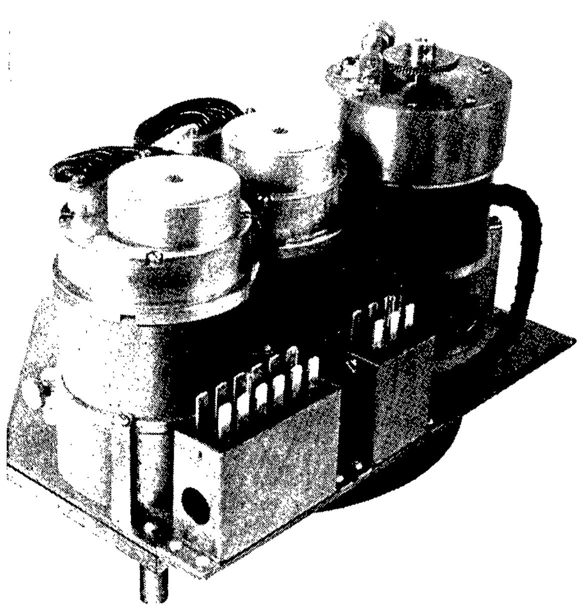


FIGURE 26. Model 5 MTB unit. Interior view.

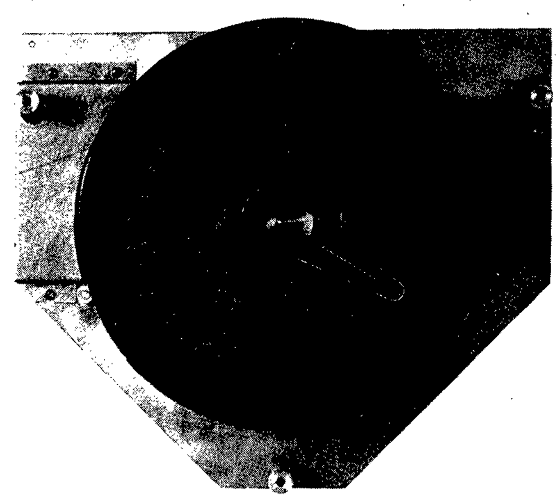


FIGURE 27. Bearing indicator of a Model 5 MTB system.

QC racks. However, in order to hasten the introduction of MTB into operating units of the Navy, parts kits were assembled for the conversion of four types of existing sonar equipment.

Two kits were made for converting RCA and Submarine Signal Company amplidyne-controlled QC gear to the MTB system described above as Model 5A. The parts included are indicated in Figure 24. Kit A was for use with systems having a 36-speed gyro, whereas Kit B (Figure 28) was for systems having a single-speed gyro. Installation and operation manuals were prepared by the Navy.

A kit was built to convert Submarine Signal Company thyratron-controlled QC gear, and another was prepared to convert WEA-1 and QCU gear. These followed the Model 5B system, as indicated in Figure 25. While the first three kits demanded only minor additions to the training motor amplifier, the WEA-1 conversion included a complete new thyratron amplifier circuit and required remachining the rotor of the existing training motor to give it more power. Details may be found in the instruction manual listed in the bibliography. None of the WEA-1 kits were installed by the Navy.

Laboratory trials and sea tests indicated that the application of MTB to RCA thyratron-controlled gear would be unsatisfactory. The reversing relays involved in this equipment would not permit smooth MTB operation.

3.9 PERFORMANCE

It was found that the need for MTB increases as the size of vessels using echo ranging decreases, because of the general instability and yawing tendencies of the small boats. It is felt that for boats as small as submarine chasers, echo ranging without the assistance of the MTB systems becomes relatively ineffective. Tests indicated that the addition of MTB to echo-ranging gear on the highly maneuverable submarine chasers produced a much more useful attack combination.

Sea tests of gear converted to MTB by parts similar to Kit A (see Figure 24) indicated a static follow-up accuracy of the entire system between ½ and ¾ degree. Operation was substantially as rapid as that of the original training control.

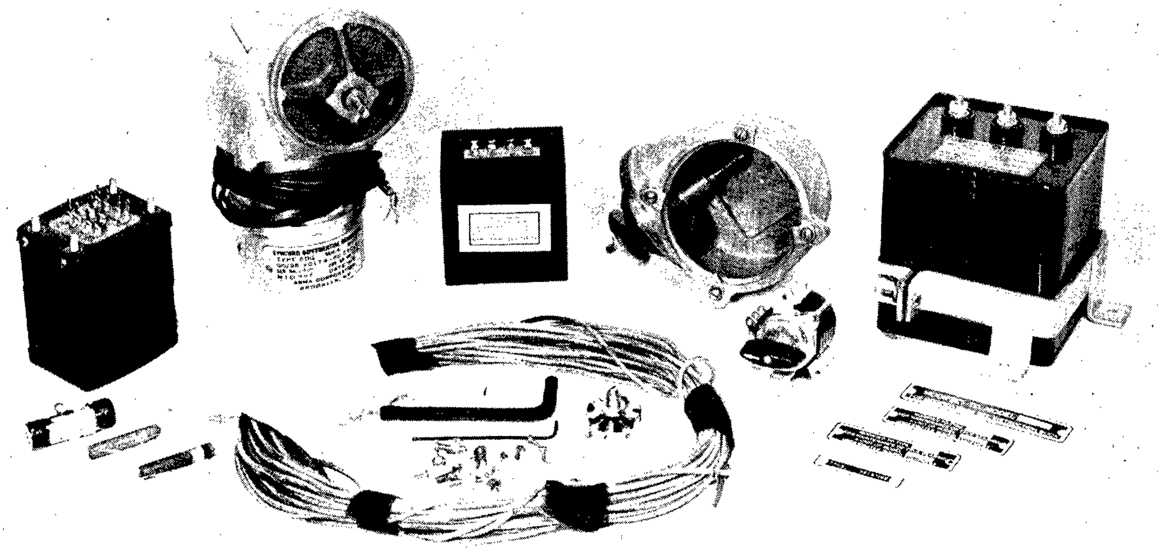


FIGURE 28. Conversion Kit B, for amplidyne-controlled QC systems having a single-speed gyro.

Electronic Automatic Search

Electronic automatic search [EAS] comprises a system of electronic circuits which, with a motor, can be employed to operate a ship's sonar transmitter and training unit automatically during the search period in accordance with a previously determined pattern in a ping-listen-train sequence. The present device is intended for use only with sonar systems having selsyn training. The EAS equipment was not adopted for Navy use because the ping-listen-train cycle was superseded by a new automatic search plan that involved continuous slow-speed training of the sonar projector. The development of electronic automatic search was carried on by the Harvard Underwater Sound Laboratory.

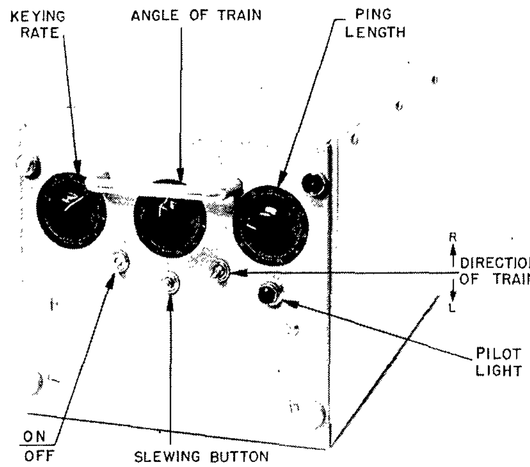


FIGURE 29. External view of experimental EAS.

3.10 GENERAL DESCRIPTION

EAS provides, with a minimum of mechanical parts, a means for training automatically an echo-ranging sonar system having selsyn training in accordance with a predetermined search plan. The circuit keys the sonar system for a ping of adjustable length, allows a listening period of adjustable length, then causes the projector to train (either to right or left, as desired) any given number of degrees, keys the next ping, and then repeats this cycle continuously. The adjustments of ping length, keying rate, degrees trained, and direction of train are operable separately and without affecting one another. The electronic circuit consists of a power supply and the components which carry out the listen-train-ping cycle. The motor provided with EAS drives the handwheel of the original manual training mechanism of the sonar system.

DEVELOPMENT

The first EAS circuit developed employed only five tubes and was supplied directly with alternating current, which was rectified in the parts of the circuit where direct current was needed. However, trouble was encountered in maintaining balance with this system, so the circuit was modified and fed from a rectifying system.

3.11 FINAL MODEL

The final EAS system (see Figure 29) has the following characteristics:

1. Keying rate continuously adjustable between $1\frac{1}{2}$ and 15 sec, corresponding to ranges above 1,250 yd.
2. Training angle for each cycle continuously adjustable between 2 and 12 degrees.
3. Ping length variable between 25 and 150 yd (30 to 180 msec).
4. Training direction reversible by means of a toggle switch.
5. Pushbutton control of slewing.
6. Simple maintenance and installation.

Subsequently, some circuit simplifications were introduced and the speed of training was increased, but further development of the EAS was terminated before these modifications could be crystallized.

DESCRIPTION OF THE CIRCUIT

The circuit illustrated in Figure 30 consists of a positive and negative power supply and components which carry out the listen-train-ping cycle of EAS. Thyratron V-4, the pulsing tube, controls the echo-ranging cycle; thyratron V-6, the motor-operating tube, controls the training section; V-5B, the relay-operating tube, controls the keying section of the circuit.

Power Supply. Transformer T-1 and tubes

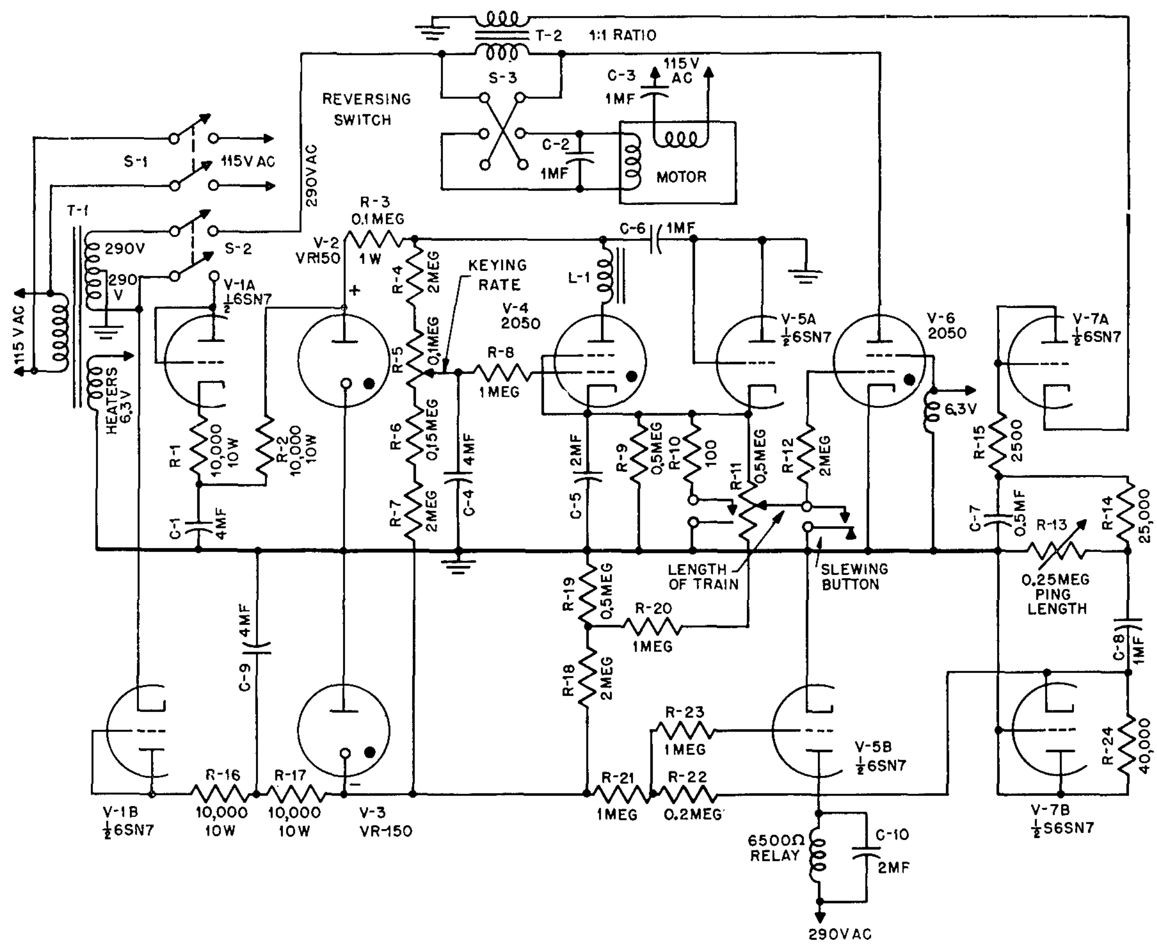


FIGURE 30. Circuit diagram of EAS.

V-1A, V-1B, V-2, and V-3 (with their filter sections R-1, R-2, R-17, R-16, C-1, C-9) constitute the power supply. This provides positive and negative 150 v direct current, 290 and 6.3 v alternating current.

Pulsing Circuit. At the beginning of the listening period, V-4, V-6, and V-5B are not conducting and C-6 is only partly charged. During the listening period, the positive supply line builds up the charge in C-6, thus raising the potential of the grid of V-4, the pulsing tube, until this tube finally fires. Part of the charge in C-6 is then immediately transferred to C-5. As C-5 becomes charged, the potential of the grid of V-6, the motor-operating tube, rises until that tube fires. The current passed by V-6 actuates the training motor.

Training Circuit. When the training motor is actuated, V-4 immediately ceases to conduct because the loss of charge from C-6 lowers the potential of its grid (the choke L-1 also helps to quench it). But V-6 will continue to conduct and operate the training motor until C-5 has lost most of its charge to ground through R-9. Of course, thyratron V-6 can pass plate current only during alternate half-cycles of the alternating current, but it is kept alive during the intervening half-cycles by 6.3 v alternating current on its screen grid, connected 180 degrees out of phase with the plate supply.

Keying Circuit. During the time the training motor operates, transformer T-2 is energized. Its secondary, acting through the rectifier system V-7A, R-15, C-7, and R-14, is building up a charge in condenser C-8. As soon as V-6 ceases to conduct, the emf in the secondary of T-2 disappears and so C-8 begins to discharge. As C-8 discharges, through R-24 and R-13 in series, the

IR drop across R-24 raises the grid potential of the keying tube V-5B until the latter conducts. The relay in the plate circuit of this tube then closes contacts of the sonar system which causes the beginning of a ping. As C-8 gradually discharges, the V-5B grid potential falls once more until the tube ceases to conduct, the relay opens, and the ping is broken off.

The listen-train-ping cycle now repeats, with most of the circuit at rest during the listening period while the charge in C-6 is building up.

Controls. The point on C-6's charging curve at which the V-4 grid reaches the firing potential may be varied by means of the sliding contact on R-5. This rheostat therefore governs the keying rate of the system. The length of the training period is governed by the slides on R-11 which determines the point on C-5's discharge curve at which the V-6 grid will fall below cutoff. The ping length may be varied by means of R-13, which controls the rate of discharge of condenser C-8. The time ranges over which these three controls may be varied depend principally on the constants built into the three timing networks involved: R-3—C-6, C-5—R-9, and C-8—R-13—R-24.

The slewing button raises the normally negative V-6 grid to ground potential and so causes the training motor to operate for as long as desired.

The switch shorting C-5 through 100 ohms is a pair of contacts on the relay which closes during the ping (after the training period is over). The shorting tube V-5A prevents the negative power supply from driving the V-4 cathode negative during the listening period, through the charging line R-18—R-20—R-11. The combined effect of the switch and V-5A is to insure that the V-4 cathode is always at the same potential (ground) when ready to pulse, regardless of the keying rate chosen.

While C-8 is being charged, tube V-7B acts as a by-pass around the 40,000-ohm resistor R-24, and so reduces the time constant of the charging circuit. This makes the final charge in C-8 more nearly the same for long and short training periods, and thus tends to make the ping length setting more nearly independent of the length of train setting.

Installation

The two-phase motor is mounted in such a way that it will drive the handwheel of the original manual training mechanism of the sonar system. Wires from the EAS relay are connected across the hand key of the system.

As soon as a connection is made to the a-c power source, the heaters and the negative power supply are energized. A slight delay is necessary before closing S-2 to protect the thyratrons from high voltage until their cathodes have come up to temperature. After S-2 is closed, about 20 sec are required for the V-4 grid to take up its operating potential. The circuit should then be in operation, although about 15 minutes are required for all the components to reach a steady temperature.

Performance

Bench tests and tests on board a laboratory vessel at sea showed that successive keying intervals were uniform within less than $\frac{1}{4}$ sec (once a steady temperature had been reached), and that the accumulated error of train was not over 3 degrees for 18 c when the device was operating on 5-degree steps. In general the circuit behaved as expected.

Not enough continuous sea duty was accumulated by EAS before the project was terminated to permit an evaluation of its ruggedness. However, a higher margin of safety would be provided by replacing the duplex 6SN7's by single tubes such as 6Y5's which are specially designed for high voltage between heater and cathode. A time-delay relay to allow the thyratron cathodes to warm up before applying plate voltage might also be desirable.

Chapter 4

SONAR DOPPLER APPLICATIONS

THE FREQUENCY SHIFT known as the doppler effect is a conspicuous feature of underwater echo ranging. The magnitude of the frequency shift arising from motion of the vessel carrying the sonar equipment impairs the freedom of the designer to utilize sharply selective circuits, whereas the smaller frequency shifts arising from target motion provide useful tactical information if the sonar operator can be trained to interpret the information. This chapter is concerned with the design of electronic equipment intended to mitigate the handicaps and enhance the benefits accruing from this phenomenon. Because all these doppler devices have a common background, it is expedient to present a description of the entire group in a single chapter.

For each device described, the design objective has been the production of equipment which could be added to sonar equipment already in service. This requirement has in many instances interfered with the attainment of compactness, reliability, and ease of operation. Since many circuit elements are common to more than one of the devices, their use in combination would result in smaller and less complex equipment. In addition, the design of such combinations would provide an opportunity for more thorough engineering than is achieved in the auxiliary units which are described.

The individual devices are presented in approximately the order of their acceptance by, and importance to, the Navy. Thus the *own-doppler nullifier* [ODN] and *doppler controlled gain* [DCG], which form the subject of the first two sections, have been generally accepted and incorporated integrally in the QGB and XQHA sonar equipment. The ODN operates to eliminate the considerable frequency shift caused by own-ship's motion and permits the use of selective circuits in the sonar receiver, whereas DCG provides for an automatic increase in the gain of the sonar receiver for dopplerized echoes having frequencies different from that established by the ODN. On the other hand, the *electronic aural responder* [EAR] is a device which received little experimental testing, since it was conceived late in the research program. It is worthy of further study, however, since it appears to be capable of producing objective responses equal to, or surpassing, the discrimination afforded by the human ear.

The *reverberation suppression filter* [RSF] constitutes a band-elimination filter intended to perform a function similar to that of DCG. The principle is sound for the purpose intended, but it does not appear to be as universally applicable as DCG. The *target doppler indicator* [TDI] presents frequency shift information on the screen of a cathode-ray oscilloscope. The device achieved its objective, but was not adopted by the Navy because the added information available to an operator did not appear to warrant the size and complexity of the apparatus involved. The *echo doppler indicator* [EDI] is essentially a vibrating reed frequency-meter which gives visual indications of the frequency shifts in reverberation and echo signals and is calibrated to read directly in range rate. In echo-ranging tests it performed as intended and, in addition, showed potential value as an analyzing device for the study of reverberation doppler. The *audible doppler enhancers* [ADE] were successful in magnifying the frequency shifts, but the methods utilized introduced so much degradation of tonal quality as to make their use unacceptable. The basic objective of ADE is sound and it is to be expected that further development along the lines recommended would yield useful results.

Own-Doppler Nullifier

The own-doppler nullifier [ODN] is a device designed to eliminate the effects of own-ship's motion from the audible signal heard on the sonar receiver. With ODN, reverberation signals received in a sonar system generate an audio frequency of a predetermined fixed value regardless of the doppler caused by the motion of the transmitting vessel. Later ODN units were of the electronic automatic frequency control type, utilizing a discriminator circuit which samples the reverberation to effect an appropriate frequency correction of the receiver oscillator. In its final form, ODN adequately fulfilled the purposes for which it was designed; i.e., to make possible (1) sharp audio filtering without operator attention, and (2) use of devices dependent on target doppler alone. The ODN equipment, in conjunction with doppler controlled gain [DCG] was approved by the Navy for installation on a number of vessels. Sea tests indicated a maximum speed of approximately 20 knots for efficient operation. The development of the own-doppler nullifier was carried out by the Harvard Underwater Sound Laboratory.

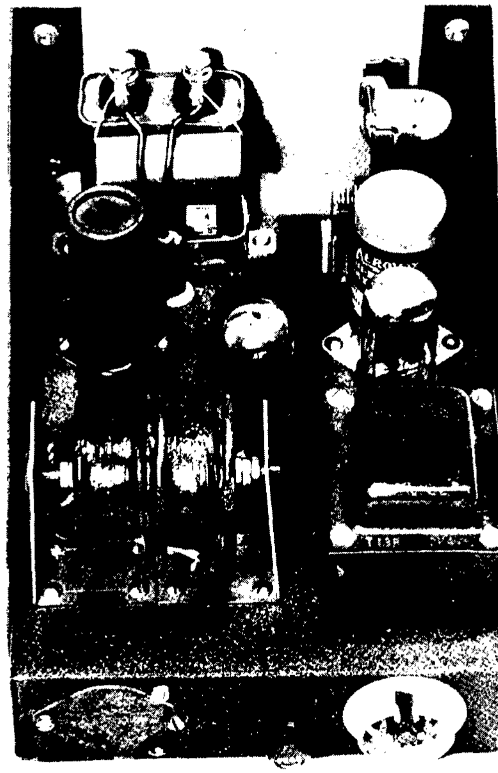


FIGURE 1. Model II-C AFC-ODN chassis.

4.1 INTRODUCTION

The purpose of the ODN is to cause reverberation signals received in a sonar system to generate an audio frequency of a predetermined, fixed value regardless of the doppler caused by the motion of the transmitting vessel.

The transmitted frequency used in the sonar devices with which this report is concerned is commonly about 20 kc. Antisubmarine vessels usually operate at speeds from 8 to 15 knots during search. For this frequency and speed range the own-doppler shifts range up to about 200 cycles per second.

In the sonar receiver the signal is usually heterodyned by a *beat-frequency oscillator* [BFO] to a frequency of 800 cycles per second. Because the transducer bearing may vary from directly ahead to directly astern, the doppler may increase or decrease the beat frequency by any value from 0 to 200 cycles per second. It is, therefore, necessary either to widen the pass band of the receiver proportionately on both sides of the center frequency or to find some method of nullifying the frequency shift produced by the ship's motion. Since the most favorable signal-to-noise ratio is secured with a narrow transmission band in the receiver at a predetermined fixed frequency, a means of eliminating the doppler produced by own-ship's motion is highly desirable. Own-doppler nullification, furthermore, is desirable in devices which utilize target doppler.

One method of neutralizing own-doppler is to vary the frequency of the BFO manually as the speed of the ship or the transducer bearing is altered. This adjustment is seldom practiced, however, as it requires some skill and the almost constant attention of the operator.

The automatic methods of securing own-doppler nullification may be classified as follows.

1. Computed-correction method.
   a. Applied to the transmitter.
   b. Applied to the receiver.

2. Automatic frequency control based on reverberation sampling.

The later ODN units are all of the electronic AFC type, utilizing a discriminator circuit which samples the reverberation to effect an appropriate frequency correction of the receiver oscillator. The first models of the reverberation controlled ODN suffered from a frequency instability which was remedied in later models by increasing the length of the sampling period. When fairly satisfactory performance had been secured, the ODN unit was combined with other devices or circuits for improving echo reception, such as TVG, RCG, RSF, TDI, and DCG. A particular combination of ODN, RCG, and RSF, known as the ERB underwent an extensive test program. At the conclusion of these tests a final chassis was developed which consists only of ODN and DCG. In its final form the ODN device adequately fulfills the purposes for which it was designed; that is, to make possible (1) sharp audio filtering without operator attention, and (2) the use of devices dependent on target doppler alone. The ODN-DCG combination received Navy approval and was adopted for incorporation in QGB, XQHA, and all later sonar equipment.

Further development work is recommended for both the computed correction and the AFC types of ODN. In the case of the former, superior operating reliability and direct indication of own-ship's speed are advantages which may be obtainable; with the latter, refinements in design leading to satisfactory operation under a wider range of service conditions seem both possible and desirable.

4.2 DESCRIPTION OF OWN-DOPPLER NULLIFIERS

4.2.1 Computed-Correction ODN Models

APPLICATION TO TRANSMITTER

The first "mechanical" ODN was designed around the special variable air condenser shown in Figure 2. The bearing cosine plates are caused to move to the right or left by a scotch yoke, the displacement of which is proportional to the cosine of the bearing angle. A selsyn repeater is used to reproduce the transducer bearing at the yoke. The speed plates are adjusted vertically by a manual control in accordance with the speed of the ship. To effect control of the transmitter frequency, the ODN condenser is connected in parallel with the tank condenser of the QC driver.

An inspection of Figure 2 will reveal how different positions of the movable plates produce the capacitance correction required for various speed and bearing combinations. Since a doppler of 200 cycles per second is a relatively small percentage of the transmitter fre-

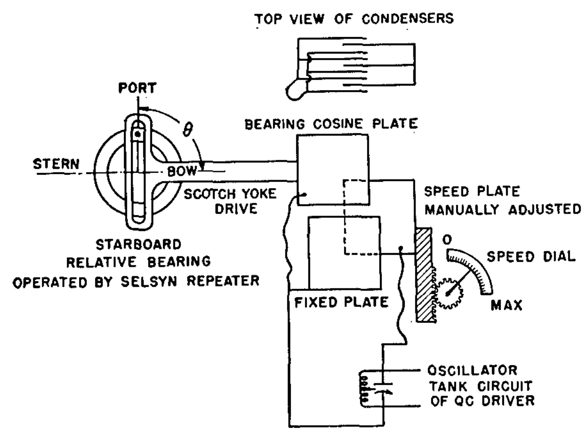


FIGURE 2. Circuit of computed-correction ODN, transmitter type.

quency (20 kc), only small changes in capacitance are required to bring about the necessary changes in transmitter frequency. The inverse relation between the capacitance changes in the ODN condenser and the corresponding frequency changes is therefore assumed to be linear. The design of the square plates, shown in Figure 2, is based on this linear relation.

Throughout the period of its use this ODN functioned satisfactorily except for a minor insulation breakdown caused by the high voltage applied to the tank condenser. Improved insulators eliminated this trouble. Manual speed adjustment was made by training the transducer rapidly from 0 to 90 degrees relative bearing while the speed control knob was turned, until a difference in pitch of the audio output was no longer heard during the rapid training of the transducer. The ship's speed

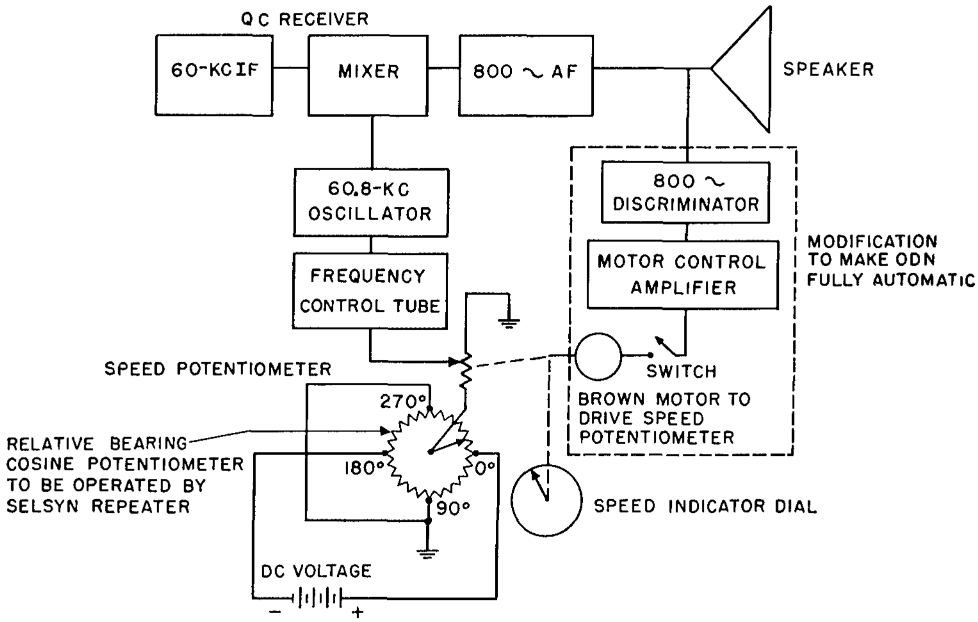


FIGURE 3. Computed-correction ODN, applied to BFO.

as determined by its revolution counter was found to agree within 0.2 knot with the speed indicated by the ODN speed control. The own-doppler nullification secured in this manner made it possible to use an audio filter without repeated adjustments of the beat-frequency oscillator so long as ship's speed and course remained constant. When these were changed, however, by action of the engine or the rudder, it was necessary to keep readjusting the ODN speed control knob to maintain accurate own-doppler correction.

In order to make the speed adjustment of the ODN automatic, it was planned to equip a speed log of the pitometer type with suitable linkages to effect the speed control. Before this project was carried out, it was realized that the electronic AFC type of ODN operating by reverberation sampling was a simpler device, so research on the mechanical ODN was terminated.

Application to Receiver

Another type of computed-correction ODN is illustrated by Figure 3. In this ODN the BFO is controlled by a reactance tube which is connected across the tank condenser. This ODN never reached a stage of development which warranted giving it sea tests. Bench performance of the device was satisfactory except for the instability which develops when the bearing potentiometer is set at 90 or 270 degrees. At these settings the output of the potentiometer is zero. Under this condition, the speed potentiometer can effect no control, and any departure from the reference frequency at the receiver output causes the motor to run to the limit of the potentiometer in an effort to make a correction. This difficulty could be cured by disabling the motor for the particular bearing angle settings of 90 and 270 degrees.

Because of the priority assigned to the electronic AFC type of ODN, the development of the combination ODN was also discontinued at the completion of the bench tests. The combination type suffers from the disadvantages of complexity and of instability when the transducer is trained abeam. It has the advantage, however, that a dial, indicating the contact position on the speed potentiometer, can be used as a ship's speed log. This is a desirable feature for ships not equipped with a speedometer. Such a speed log, moreover, is not affected by rudder action. A comparable means of indicating ship speed in a simple manner had not been developed for the AFC types of ODN up to the time of writing.

4.2.2 Automatic Frequency Control ODN

Model I

Automatic frequency control consists essentially of a balanced self-correcting system in which a variation of the output frequency is

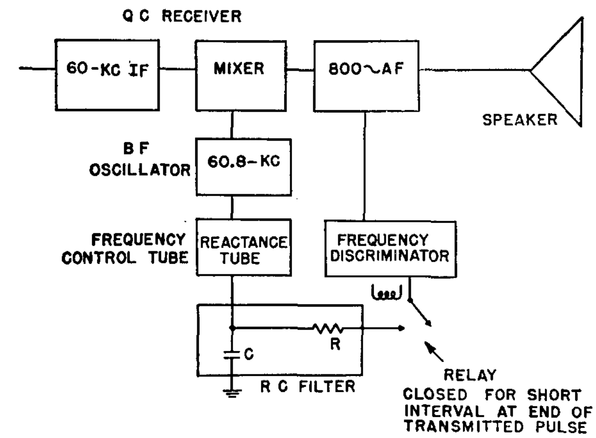


Figure 4. Block diagram of electronic AFC type of ODN.

reflected into the system to effect a return to the original output frequency. Figure 4 illustrates a method by which AFC principles may be applied to an ODN system. The input for the AFC circuit is derived from a receiver in which the incoming signals are heterodyned to an in-

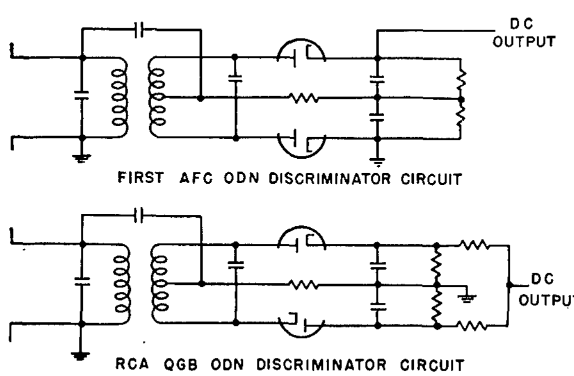


Figure 5. ODN discriminator circuits.

termediate frequency of 60 kc. After amplification, the intermediate frequency is again heterodyned by the BFO to an audio frequency of 800 cycles per second.

The action of this circuit tends to keep the receiver audio output at a constant frequency of 800 cycles per second despite slight variations in the intermediate frequency. The accuracy of this balanced system depends both on the volts-per-cycle-per-second deviation developed by the frequency discriminator and the cycle-per-second-per-volt correction obtained from the reactance tube. The output of the discriminator is applied to the reactance tube through contacts controlled by a relay. An RC filter is also included in the circuit (see Figure

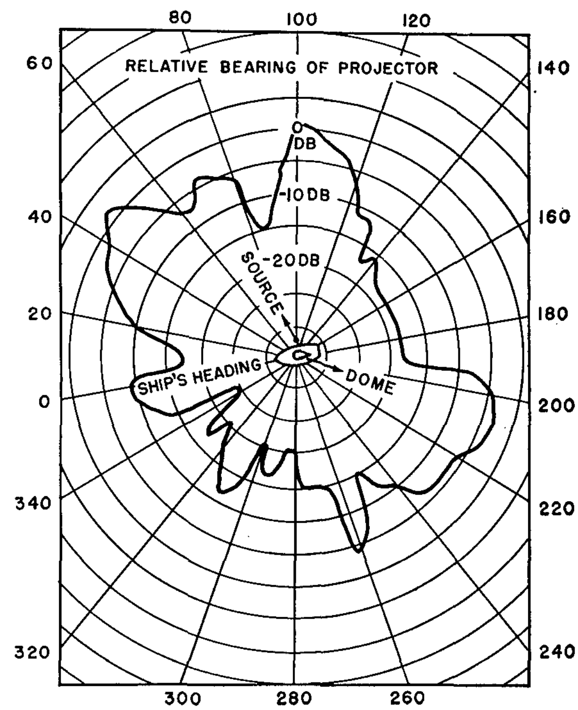


Figure 6. Projector receiving pattern.

4). The functions of the relay contacts are (1) to restrict the time in which the frequency correction is made to a short interval immediately following the transmission of a ping, when the reverberation signal is strongest, and (2) to prevent the condenser charge from leaking off through the discriminator components after reverberation has ceased. To prevent a dopplerized target echo from disturbing the AFC system, the relay was first adjusted to restrict the correction interval, or sampling time, to a range of not over 30 yd. In succeeding models this was increased to 60 yd, and as explained later, still longer sampling times were ultimately found desirable.

The first ODN of the AFC type consists of a Foster-Seeley frequency discriminator circuit and the necessary relays to provide the proper correction sequence. An improved variation of this circuit is used in later ODN models, including the one finally installed in the RCA-QGB equipment. The essential difference between the two versions lies in the method of connecting the rectifiers, as shown in Figure 5. A comparison of the diagrams indicates that the first ODN circuit will give two or three times as much d-c output voltage, for a given a-c input, as will the revised circuit. The first circuit, however, is not symmetrical. Reverberation irregularities, because of excessive generation of transients, are much more likely to produce fluctuations in the output of this circuit than in the one which was adopted later.

Model II

Tests of the first automatic frequency control ODN led to the conclusion that limiting and power amplification before the discriminator were needed. The added power required for these tubes made it necessary to provide a separate power supply. The second model of ODN, incorporating these modifications has its own power supply, two stages of limiter amplification, and a power amplifier. A metering tube for a *target doppler indicator* [TDI] and *time-varied gain* [TVG] (see Section 2.2) are also included in the chassis. Tests of one of these units proved it superior to the previous model. The overall performance of the second model, however, was in general not satisfactory because of poor projector beam patterns. A polar

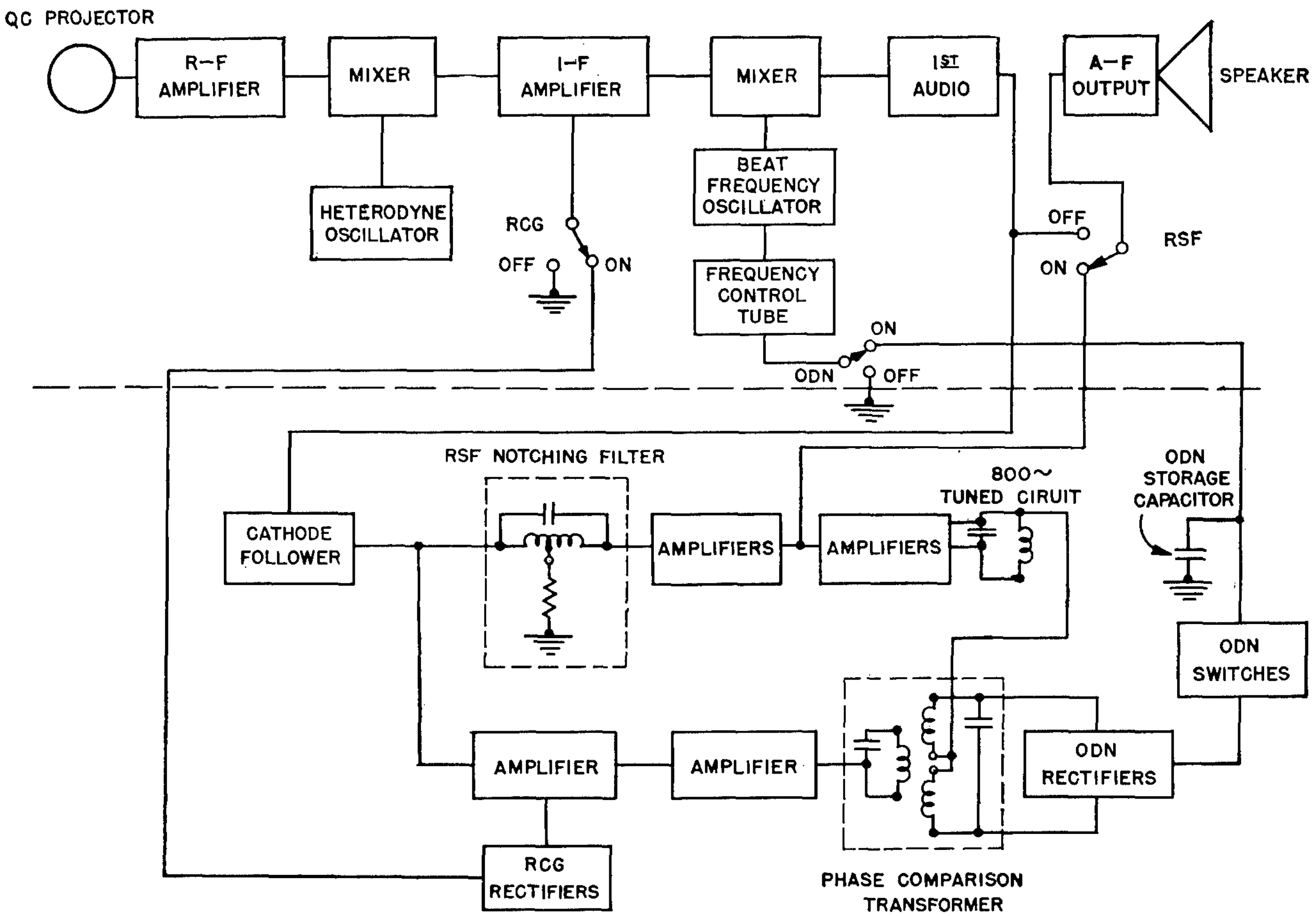


FIGURE 7. Block diagram of echo-ranging booster.

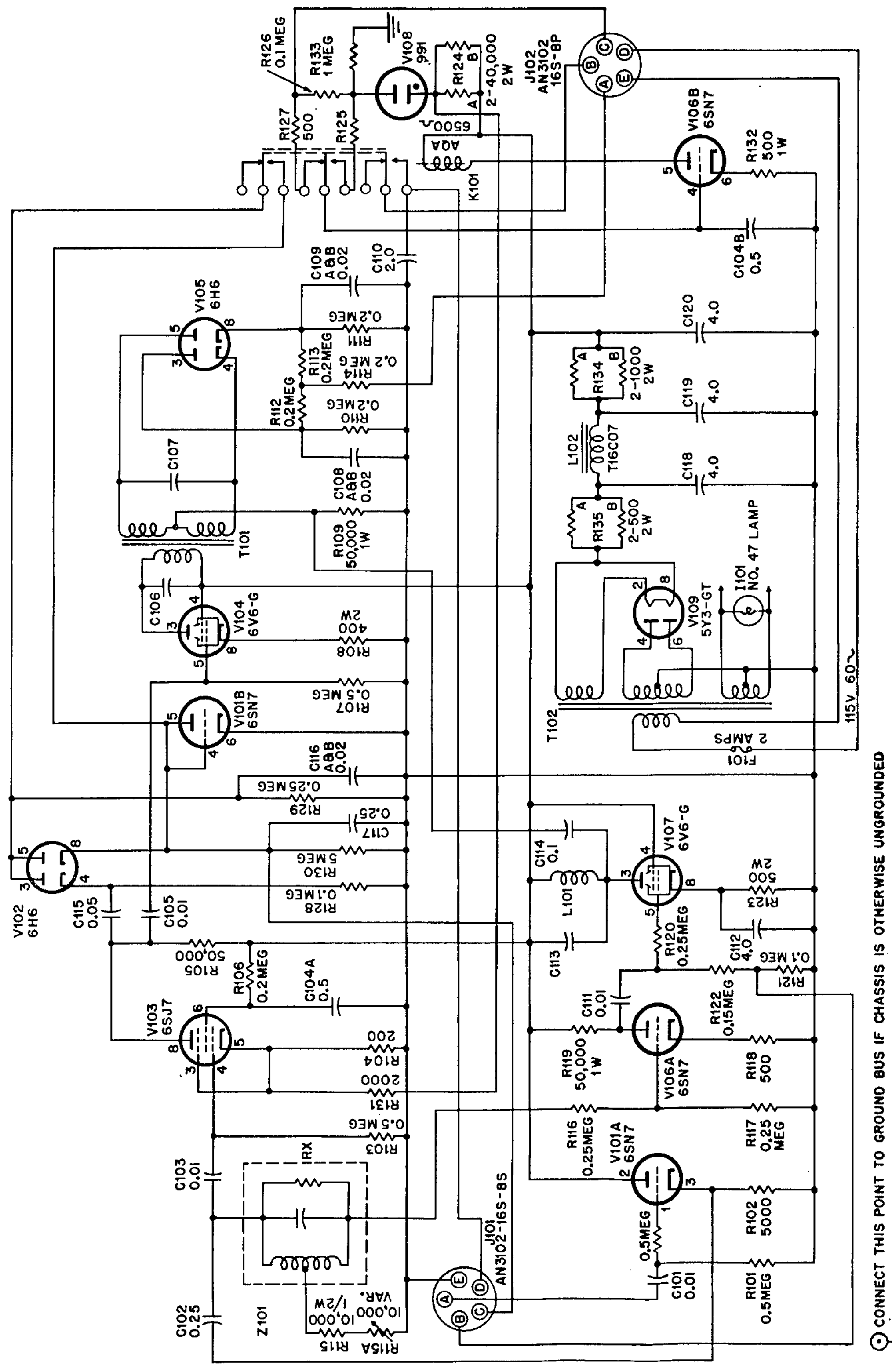


FIGURE 8. Schematic diagram of echo-ranging booster Model I

sensitivity plot for the projector used (Figure 6) shows side lobes at 60 degrees practically equal in intensity to the major lobe. This produced two distinct tones in the reverberation so that the ODN frequently responded to the wrong one.

ODN IN THE ERB UNIT

In its next stage of development the ODN unit was combined with the *reverberation suppression filter* [RSF] and the *reverberation-controlled gain* [RCG] (see Section 2.5), the combination being called the *echo-ranging booster* [ERB] (see Figures 7 and 8). Although the ERB performs three distinct functions, its three circuits are interconnected and share certain components. Thus the RSF is connected to the audio amplifier of the QC receiver in such a manner that it serves both to remove the 800-cycle-per-second component of the audio signal and to act as one of the frequency sensitive elements in the ODN discriminator circuit.

The ERB was subjected to a comprehensive testing program which included variations in discriminator circuits, sampling intervals, filter time constants and output relays. The results obtained form the experimental basis for the analysis of ODN circuits which follows below.

4.2.3 Determination of ODN Circuit Constants

FOSTER-SEELEY FREQUENCY DISCRIMINATOR

To explain the operation of the Foster-Seeley frequency discriminator reference will be made to the schematic diagram of Figure 9. The input signal voltage, E_s, is applied to the transformer, T-101, whose mutual inductance (M) is such that the windings are over-coupled to a considerable degree. The reactance of C-4 is much less than the resistance of R-11 with the result that voltage E_1 is practically the same as voltage E_p across the primary of the tuned transformer.

For a circuit of this type,[2] the phase and magnitude variation of voltage E_1 corresponding to frequency variations in the signal voltage E_s are approximately as shown by the locus graph of Figure 10A. The circle diagrams in Figure 10 were obtained experimentally by using an oscilloscope and a Ballantine electronic voltmeter. The phase and magnitude relations of E_2 and E_3, the transformer secondary voltages, are similarly indicated for different frequencies of E_s by the locus graphs of Figure 10B.

The a-c voltages, E_A and E_B, reaching the diodes, V-3A and V-4A, are the vector sums: $\mathbf{E}_A = \mathbf{E}_1 + \mathbf{E}_2$, and $\mathbf{E}_B = \mathbf{E}_1 + \mathbf{E}_3$. Figures 10C, 10D, and 10E illustrate these vector additions at resonant, low, and high frequencies, respectively. By means of the two diodes, V-3A and V-4A (see Figure 9), these a-c voltages are rectified in such a manner that the d-c output

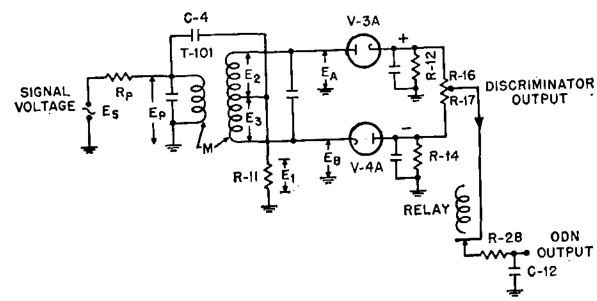


FIGURE 9. Schematic diagram of Foster-Seeley discriminator.

of the discriminator is positive for frequencies above resonance, zero at reasonance, and negative for frequencies below resonance. Figure 11 shows how the output voltage varies with the frequency of the input.

The ODN voltage is obtained from the discriminator circuit via the comparison network, R-16 and R-17 (see Figure 9). Voltage from the network is applied to the ODN relay, which, in the latest models, is closed for a period of about 380 msec following each ping transmission. While this relay is closed, the ouput of the discriminator circuit is connected from R-16 and R-17 through the half-section filter, R-28 and C-12, to the frequency control tube. The BFO frequency is varied by the automatic control thus established to maintain a frequency very close to 800 cycles per second in the reverberation audio output of the sound receiver.

At the conclusion of the 380-msec period, the relay opens, breaking the AFC feedback loop, and leaving only the charge on C-12 to hold the

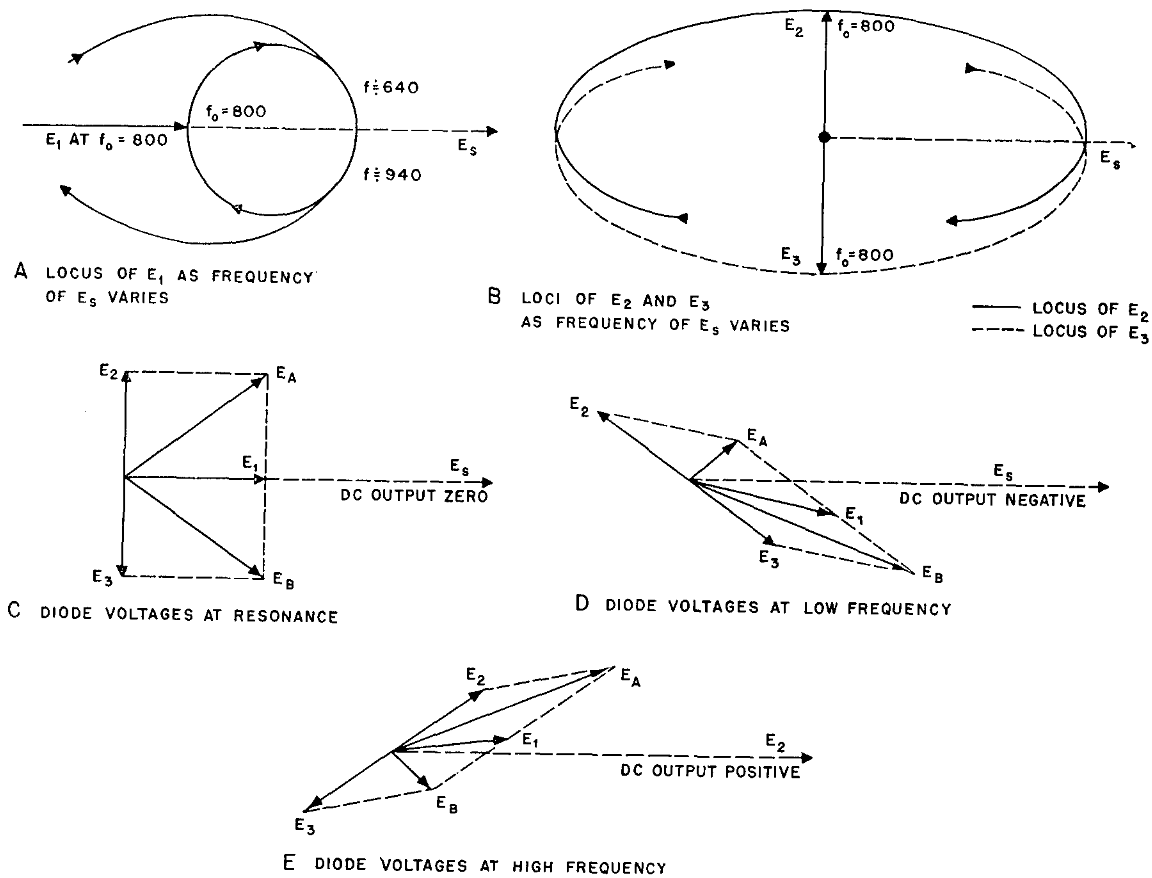


FIGURE 10. Voltage loci for Foster-Seeley circuit.

grid of the frequency control tube at the correct voltage until the relay again closes. This break in the circuit is designed to limit frequency control operation to the period when the predominant incoming signal is the reverberation from an emitted ping.

BROOKS-SEBRING DISCRIMINATOR

The frequency discriminator circuit used for the ODN in the ERB assembly is a modification of the Foster-Seeley circuit. The essential feature of the modified circuit, known as the Brooks-Sebring discriminator, is the use of the RSF to bridge the primary and the secondary of the discriminator transformer instead of the condenser used in the Foster-Seeley circuit. Figure 12 is a functional diagram of the modified discriminator. The higher sensitivity at crossover of the Brooks-Sebring circuit results mainly from the phase reversal at resonance experienced by the bridged-T filter voltage. In the Foster-Seeley circuit, the voltage vectors near resonance are approximately at right

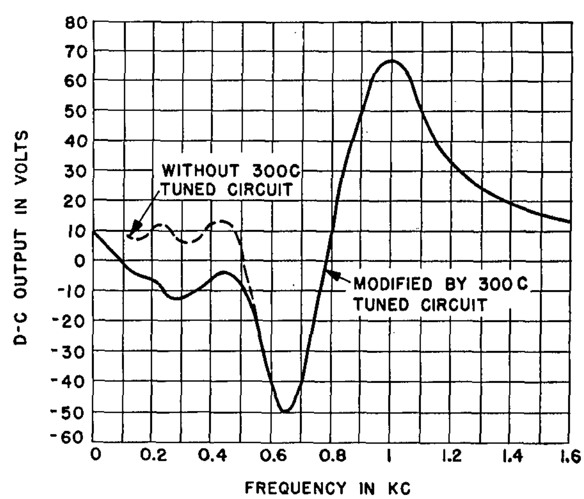


FIGURE 11. Characteristics of modified Foster-Seeley circuit.

angles and not in either aiding or opposing orientations as in the Brooks-Sebring circuit. The sensitivity of the Foster-Seeley discrimina-

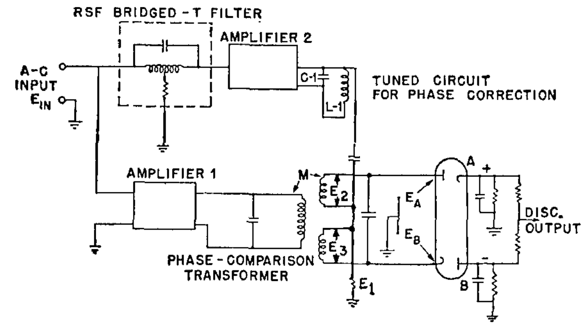


FIGURE 12. Functional diagram of Brooks-Sebring discriminator.

tor at the crossover point is consequently much less than in the Brooks-Sebring modification.

The performance characteristics of these dis-

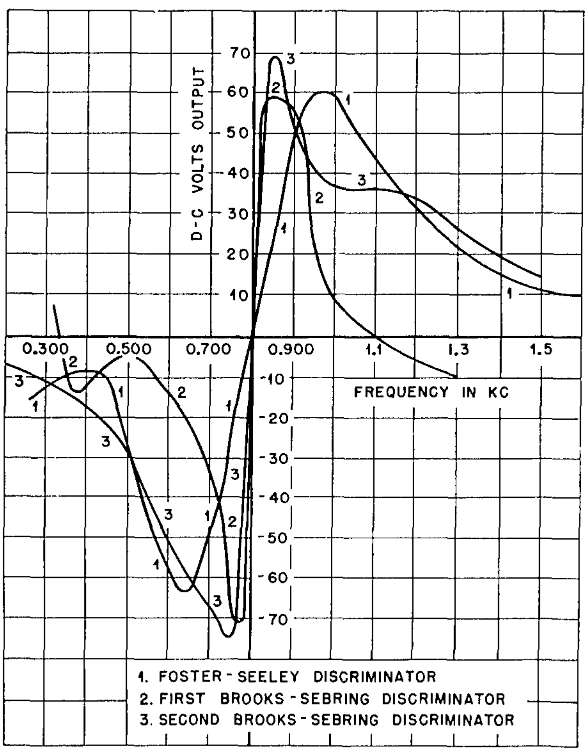


FIGURE 13. Performance characteristics of discriminators.

criminators are indicated by the curves of Figure 13. The improvement is secured by using a phase-comparison transformer with considerably higher inductances. Figure 14 shows the connections of the second type of transformer used. The curves show that the change in transformers broadens the frequency characteristic of the ODN sensitivity by increasing the output voltage for large frequency shifts. As a result the new circuit affords a more rapid correction of the beat frequency for wide frequency deviations.

FILTER CONSTANTS

The choice of components in the RC half-section filter in the ODN circuit is influenced by several factors. The value of C has its minimum definitely set by (1) the insulation resistance between the high side of the filter circuit and ground, (2) the voltage sensitivity of the reactance tube, and (3) the allowable frequency drift of the oscillator controlled by the ODN. In the ODN units actually constructed, the

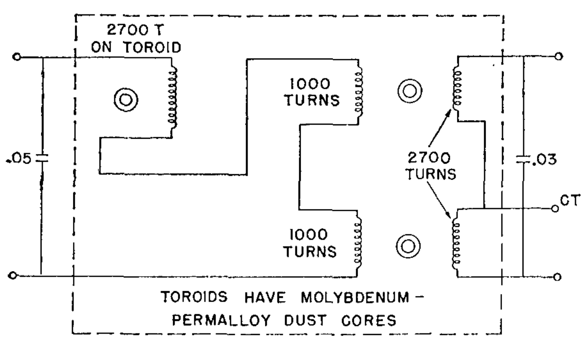


FIGURE 14. Phase-comparison transformer circuit.

sensitivity of the frequency control tube is of the order of 100 to 200 cycles per second per volt applied. From experience in damp climates, such as Key West, Florida, it has been found that 4 μf is the safe minimum for C, if the frequency of the oscillator is not to drift more than 5 to 10 cycles per second during a 5,000-yd range interval between pulses.

R should have the lowest value that can prevent the output frequency from wandering more than ± 5 cycles per second from the normal frequency as the reverberation fluctuates. In the 800-cycle-per-second discriminator circuits utilized in the ODN units, the peak value of the a-c component in the discriminator output pro-

duced by reverberation fluctuations is found to be of the order of 40 to 60 v, the average value being about 20 to 30 v. These values are affected somewhat by the deviation sensitivity of the discriminator and by the maximum voltage output of which the discriminator is capable. With a control tube sensitivity of 100 cycles per second per volt and a requirement that the output frequency not vary more than ±5 cycles per second, the RC filter must reduce the peak of the a-c component to a maximum value of 0.5 v. If the ODN relay opens during one of the 0.5-v peaks, the frequency deviation of the BFO from the ideal value will then not exceed 5 cycles per second.

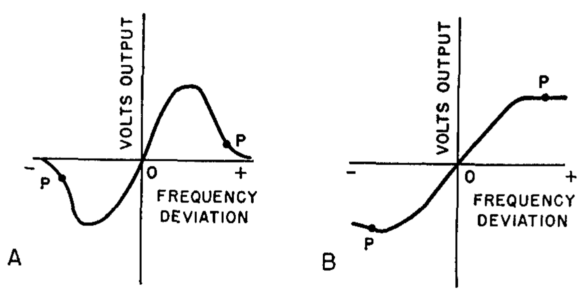


FIGURE 15. Discriminator characteristics.

The preferred method of improving the wide deviation correction rate is to retain the single RC half-section while increasing the voltage output of the discriminator at frequencies beyond the linear range. The graphs of Figure 15 indicate the nature of the desired frequency characteristics. A discriminator functioning in the manner illustrated by graph B would provide a much more rapid correction rate than one operating according to graph A. Efforts to improve ODN characteristics have all been directed toward raising the discriminator output voltage for wide frequency deviations, as in the Brooks-Sebring discriminator. The half-section filters used in all the later ODN models have R ranging from 0.5 to 1.5 megohms with C equal to 4 μf.

ACCURACY OF ODN FREQUENCY CORRECTION

It is found that the stability of an ODN circuit is a function of the voltage sensitivity of the frequency control tube and the deviation sensitivity of the discriminator. The least sensitive reactance tube that will cover the required frequency range from 0 to 1,500 cycles per second is found to have a sensitivity of about 100 cycles per second per volt applied. In the interest of stability, therefore, the discriminator should have as low a deviation sensitivity as practicable. The lowest practicable value in any given case depends on the accuracy of correction required.

It may be shown that the accuracy of correction approximately equals $1/KS$, where K equals the frequency control sensitivity and S equals the discriminator sensitivity. Common values for K and S are 100 cycles per second per volt and 0.7 v per cycle per second, respectively. With these values the accuracy $1/KS$ is about 1/70. The reciprocal of the accuracy, KS, may be spoken of as a "figure of merit" which in this case is about 70. The deviation in output frequency at equilibrium will be, accordingly, 1 cycle per second per every 70 cycles per second of frequency deviation in input.

In ODN operation, input frequency deviations of 500 cycles per second are possible at high speeds. With such deviations the output deviation after correction is $500/70 \doteq 7$ c.

If an additional 5 cycles per second is allowed for "hunting," an ODN utilizing the values listed above will vary 12 cycles per second in its output frequency about the center frequency. The highest permissible variation is about 15 cycles per second, so that figures of merit below 50 are not desirable. With a control tube sensitivity of 100 cycles per second per volt the discriminator sensitivity should therefore not be less than 0.5 v per cycle per second.

FREQUENCY CONTROL TUBE CIRCUITS

Two different frequency control tube circuits have been used in the ODN units. The first is one applied to a receiver in which the tank circuit of the BFO has a relatively high impedance; the second is particularly suited for receivers having a relatively high capacitance (and, therefore, a correspondingly low impedance) in the BFO tank circuit. The behavior of both these frequency control circuits is anal-

ogous to that of a variable resistor in series with a fixed condenser, the combination being connected in parallel with the BFO tuning condenser (see Figure 16).

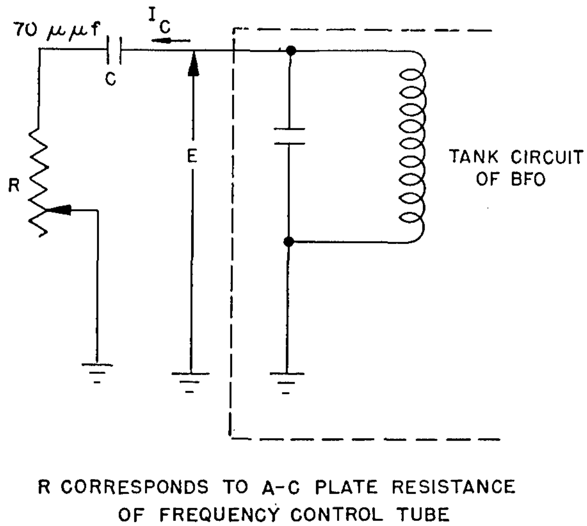


FIGURE 16. Equivalent circuit of frequency control tube for high-impedance tank.

The first frequency control circuit is shown in Figure 17. The effective a-c plate resistance of the control tube, which is a function of the

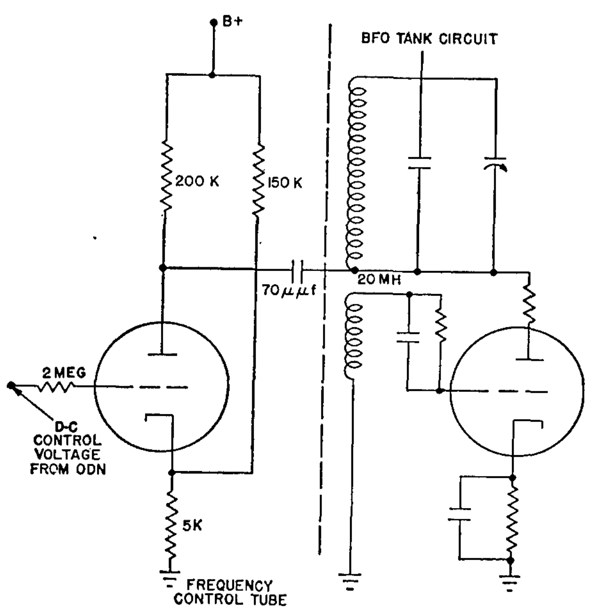


FIGURE 17. Frequency control tube circuit.

grid bias, is seen to be in series with the 70-$\mu\mu$f capacitance. As the effective resistance of the control tube is decreased, the leading component of the current drawn from the tank circuit is increased, and the frequency of the BFO decreased. The resistance of the control tube

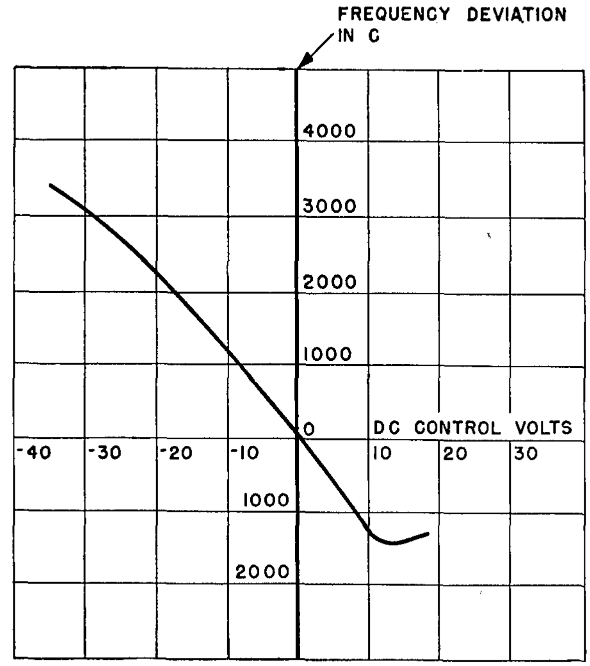


FIGURE 18. Typical reactance tube performance curve.

causes some dissipation of oscillator power but not enough to affect the operation of the sonar receiver appreciably.

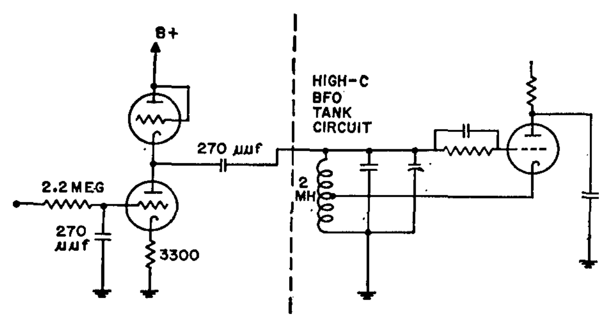


FIGURE 19. Frequency control tube circuit for low-impedance tank circuit.

Figure 18 shows a typical performance curve for a frequency control circuit of the type described above.

The second frequency control circuit is given in Figure 19. In this circuit both the condenser reactance and the effective resistance of the

control tube must be smaller than those of the first circuit because larger currents must be drawn to effect the necessary frequency changes in the low-impedance tank circuit.

SAMPLING TIME

In the early model of ODN the sampling time was made relatively short (38 msec or 30 yd). This was necessary since the time constant of the RC filter in the AFC was also relatively short. With a short time constant in the filter, a long sampling time would have two undesirable effects: (1) dopplerized echo would tend to be blanked out, and (2) the AFC system would be disturbed by the echo doppler.

It was found, however, from a number of operational tests, that the ODN operates more satisfactorily as the sampling time is increased. If the ODN sampling time is much less than 250 msec (200 yd), it will obviously not receive a proper sample of the dopplerized frequency it is designed to correct. The later ODN models were therefore arranged to have sampling times of the order of 300 msec. To lessen the interference between dopplerized echoes and the AFC circuit of the ODN, RC filters with long time constants were used. The time rate of change of the beat frequency under these conditions was too slow either to affect or to be affected by the dopplerized echo pulse to any great extent.

4.2.4 ODN Sequence Control Circuits

RELAY CIRCUITS

In adapting the ODN to the requirements of the ERB, several methods of applying the frequency discriminator output to the grid of the reactance tube were developed. In the first ERB the connection was made by means of a relay which was closed while the pulse was being transmitted and which remained closed for approximately 100 msec after the pulse transmission. Since it is the reverberation frequency rather than the transmitter frequency that is to effect the correction of the beat-frequency oscillator, an additional contact was placed on the QC speaker relay, which opened the AFC circuit during the time of pulse transmission. A detailed diagram showing the operation of these relays is given in Figure 20.

RELAYLESS ODN

Following the recommendation of the Navy, an ODN circuit was designed in which the relay was eliminated. Figure 21 is the schematic

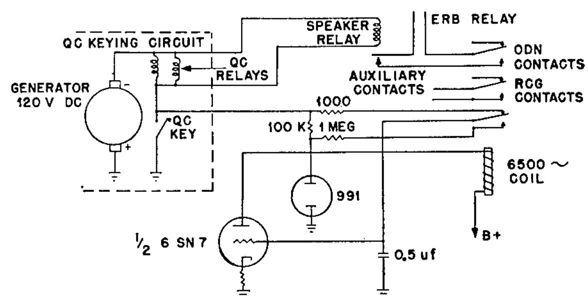


FIGURE 20. Relay delaying circuit, ERB Model I.

diagram of the electronic switch that replaces the ODN relay. In this circuit two 6SN7 triodes, connected with the cathodes and plates opposing, operate as grid-controlled rectifiers and function as the electronic switch. The d-c control voltage for the two grids is derived from 6H6 diode rectifiers which are respectively

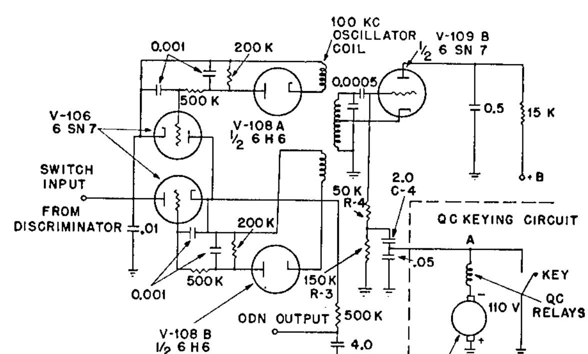


FIGURE 21. Electronic switch for relayless ODN.

fed by two isolated secondary coils coupled to an oscillator tank coil. In this manner a separate control bias independent of ground is supplied to the grid of each of the 6SN7 tubes. As long as the oscillator exciting the tank coil

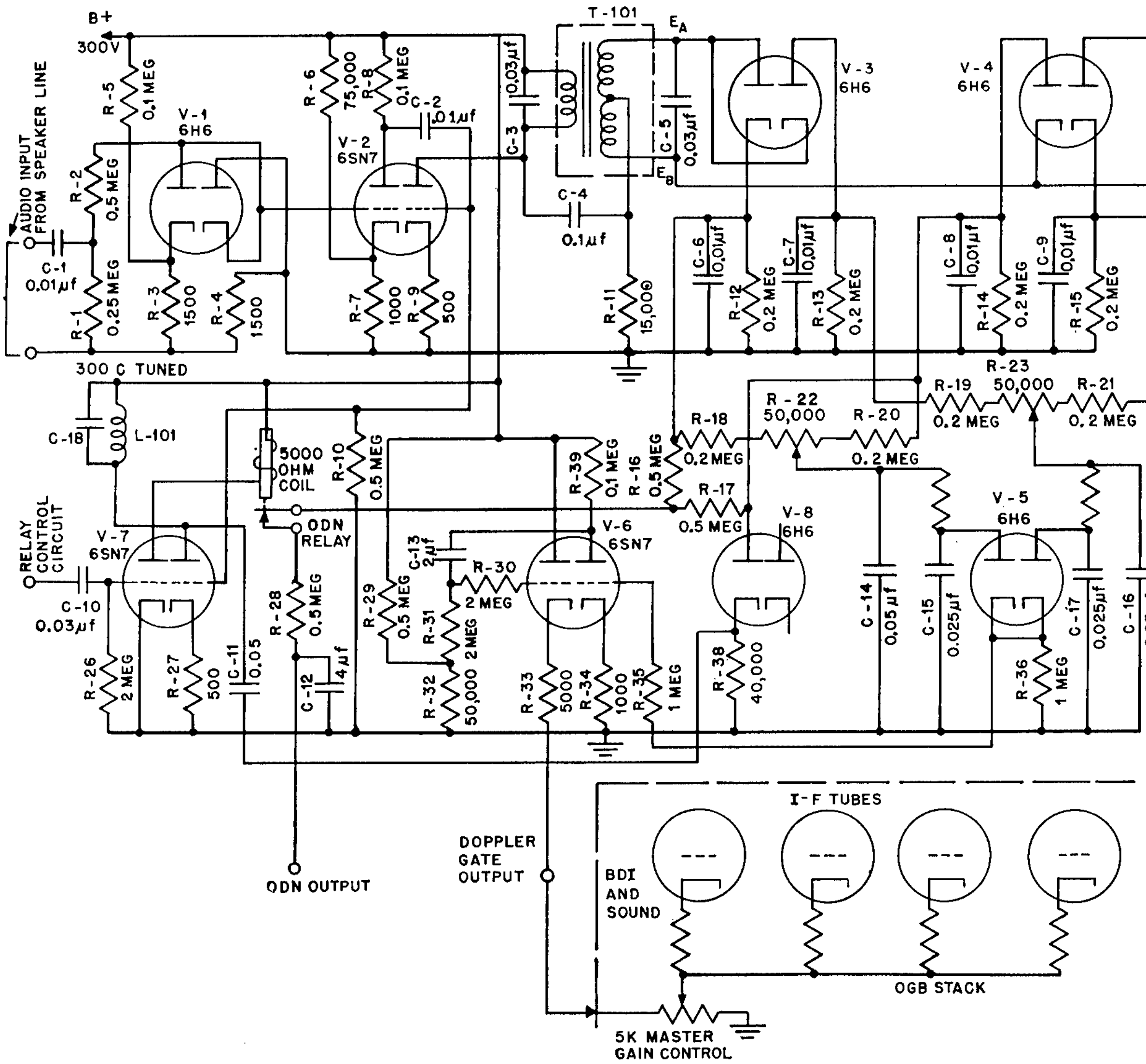


FIGURE 22. Schematic diagram of DCG and ODN for RCA-QGB receiver.

is operating, each of the grids receives a voltage which is negative relative to its cathode, so that the tubes are nonconducting. If, however, the oscillator is blocked by any means, the 6SN7 plate circuits become conducting.

Blocking of the oscillator is brought about by the opening of the key in the QC keying circuit. Opening this key produces a negative pulse which is transmitted to the oscillator through an RC filter. The time constant of the filter determines how long the oscillator remains blocked. As the pulse is dissipated, the oscillator resumes operation, thereby building up the negative voltages for the 6SN7 grids to reopen the ODN circuit. For rapid operation of the ODN it is necessary to have a relatively high oscillator frequency so that the rectifier filters do not produce too much lag.

4.2.5 Final ODN-DCG Combination

At the completion of the ERB testing program a final chassis was evolved which included only ODN and *doppler controlled gain* [DCG]. Figure 22 is the schematic diagram of this unit. The discriminator circuit is of the Foster-Seeley type. In the discriminator amplifier output

stage, a circuit tuned to 300 cycles per second has been included to increase the d-c output of the discriminator at low frequencies, and thereby prevent secondary zero crossovers.

The graph of Figure 11 shows the characteristics of the modified discriminator circuit. In order to make discriminator sensitivity and crossover frequency as independent as possible of amplitude variations in the audio receiver output, a limiter stage, utilizing a diode clipper, is located ahead of the discriminator amplifier.

In sea tests of this unit it was found that the noise level encountered at 30 knots was too high for satisfactory ODN performance, but successful results could be obtained at 25 knots. Since the test vessel was equipped with a special 100-in. dome and since the noise level would probably increase with a smaller dome, it appears that 20 knots is probably the maximum speed at which adequate performance of this type of ODN can be expected.

The ODN-DCG combination chassis was accepted by the Navy for installation in the latest types of sonar equipment under procurement at the time. Plans were made for altering all RCA-QGB equipment to include it and production was started on a conversion program involving about 500 units. At a somewhat later date, incorporation of the device in the new XQHA scanning sonar under development by the Sangamo Electric Company was also given approval.

4.3 FUTURE DEVELOPMENT

The computed-correction type of ODN applied to the transmitter is in working order. It would be of value to carry out the project of coupling to this ODN a pitometer log for automatic speed adjustment, and to compare the results obtained in this manner with those secured by the latest AFC model. The computed-correction type of ODN has the advantage of not being subject to the frequency fluctuations present in reverberation.

It would also be desirable to determine the possibilities of linking a pitometer log to the speed potentiometer of the second type of computed-correction ODN, which applies the frequency correction to the receiver. The bearing potentiometer drive should be modified to eliminate the instability found when the projector training is abeam. It is possible that in a sonar system which is stabilized against pitch and roll the performance of this type of ODN may compare favorably with that of the other types.

An ODN of the type just discussed may also be useful as a separate unit in a scanning [QH] system in which a separate receiving beam is always directed forward. The ODN could then serve as a speedometer as well as a device to provide frequency correction. There is also a possibility that an ODN could be of use in the scanning channel of a QH system. The sine wave sweep voltage could be modified by a speed potentiometer and then passed to the grid of the reactance tube.

It is possible that additional work on frequency discriminator circuits will uncover a circuit with characteristics more suitable to the needs of automatic frequency control ODN than the present one. The Navy has recently expressed an interest in an audio frequency of 500 cycles per second instead of the currently used 800 cycles per second. Such a change would seriously handicap the present AFC type of ODN. It is possible, however, that a 60-kc discriminator may be developed with a sensitivity of 0.25-v per cycle per second deviation. An ODN having such a discriminator might be coupled to the first heterodyne oscillator. The advantage of such an arrangement is that the intermediate frequency may be accurately tuned to the i-f amplifier and that the BFO can then be adjusted to produce any desired audio frequency.

Finally, there remains the problem of developing a satisfactory ODN and RSF combination, which will perform adequately under all conditions of service, including extreme variations in temperature.

Doppler Controlled Gain

Doppler controlled gain [DCG] is a system whose function is to enhance selectively the intensity of echoes returned from moving targets. The trained ear of a sonar operator can readily detect, in the echo from a target in motion, the very small increase or decrease in frequency (known as up-doppler or down-doppler) resulting from the motion of the target toward or away from the transmitting projector. DCG circuits were designed to utilize this doppler shift for the purpose of increasing the intensity of dopplerized signals in sonar receivers and auxiliary equipment. Their operation depends upon a frequency discriminator arrangement which gives an output proportional to the doppler shift in the target echo. This output is used to increase the gain of the receiving amplifier and thus enhances the relative strength of the echo signal. Under proper conditions, a 6- to 10-db increase in the gain of a BDI sound receiver may be brought about through the action of a strongly dopplerized signal. False doppler filters are included in the circuit to eliminate doppler effects caused by reverberation. The performance of DCG circuits has been sufficiently satisfactory to justify their adoption, in combination with the own-doppler nullifier [ODN], for inclusion in the latest QCB and XQHA sonar gear. Doppler controlled gain was developed by the Harvard Underwater Sound Laboratory.

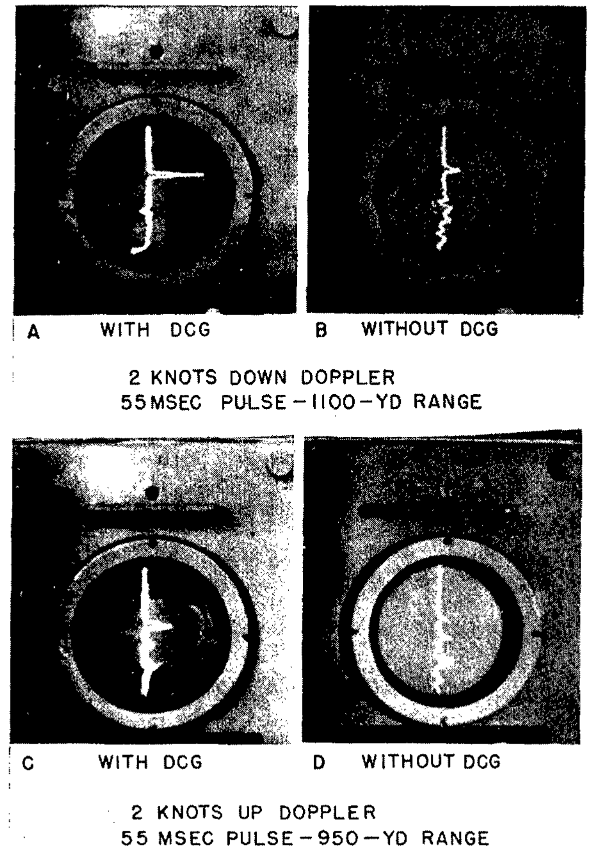


FIGURE 23. Comparative BDI traces, with and without DCG.

4.4 INTRODUCTION

The very small increase or decrease in frequency which results from motion of a target towards or away from the transmitting projector is of great assistance to the sonar operator in aiding recognition of an echo against its background of noise and reverberation. Increase in the relative intensity of dopplerized signals, so that they may be more readily perceived and evaluated, is the purpose of the doppler controlled gain circuits.

These DCG circuits first feed incoming signals into a frequency discriminating network which gives an output proportional to whatever doppler shift may be present. After being suitably filtered and amplified, this output is then used to increase the gain of the receiver amplifiers or to actuate a range recorder. In this manner, a dopplerized echo receives favored treatment over nondopplerized reverberation and noise. For satisfactory results it is usually necessary to include ODN circuits to eliminate any effects from dopplerized reverberation. However, in submarine installations, it is possible to omit ODN since only small own-doppler shifts can result from the slow movements of these vessels when submerged.

The performance of DCG circuits has been sufficiently satisfactory to lead to their adoption, in combination with ODN, for inclusion in the latest QGB and XQHA sonar equipment. However, it appears that operation in the presence of high noise levels might be improved and this problem is recommended for further study. Moreover, the provision of enhanced gain for

either individual BDI channel when carrying a dopplerized signal has been suggested as a possibility which might afford valuable operational features.

4.5 PRINCIPLES OF DOPPLER CONTROLLED GAIN

The application of DCG is greatly simplified if the frequency of the incoming reverberation can be established at some fixed value. This can be accomplished through the installation of an ODN circuit, which maintains the reverberation output from a receiver at a nearly constant frequency by compensating for the doppler shifts produced by own-ship's motion.

With the ODN circuit establishing a reference frequency of 800 cycles per second for the reverberation, the DCG circuit operates to increase the gain of the amplifier for any echo differing in frequency from the 800 cycles per second by an appreciable amount. Figure 24 is a block diagram showing the essential components of the ODN and the DCG circuits, and their relationships to a typical sonar equipment with BDI. The circuit of output No. 1 of the frequency discriminator is so arranged that an increase in the input frequency causes the output voltage to become more positive. The circuit of output No. 2 on the other hand, is connected so that a decrease in input frequency of the input produces a more positive output voltage. The doppler pulse valve consists of two diodes so arranged that they can feed only positive voltages into the gain-controlling amplifier. A voltage delay circuit is also provided so that a positive pulse is not passed on to the amplifier unless a doppler corresponding to a target speed of at least 1.5 knots is applied to the circuit. The gain-controlling amplifier is connected to the i-f amplifier in the BDI or in the sound re-

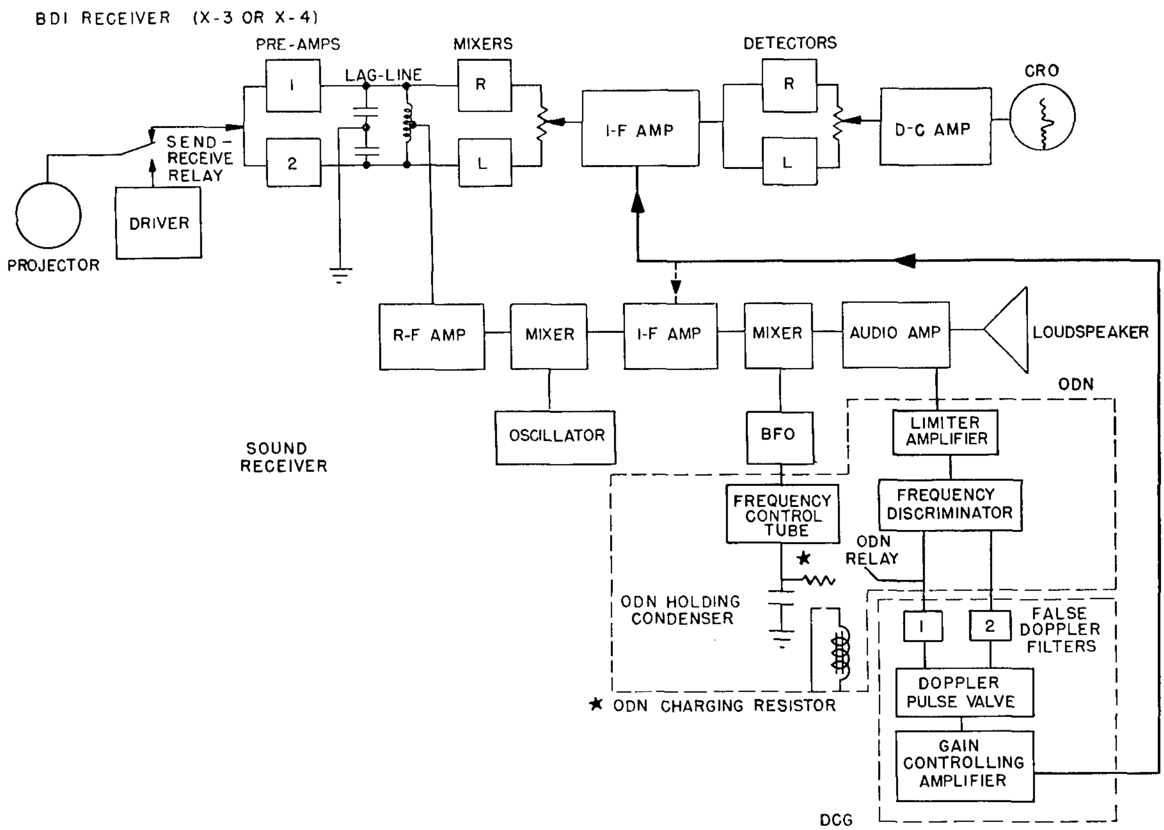


FIGURE 24. Block diagram of doppler sensitized sonar gear.

ceiver circuit so that a positive pulse reduces the bias on the i-f tubes thus increasing the gain.

The limiter amplifier reaches its maximum output at an input level of about 6 volts rms. Its limiting characteristic is made flat so that the discriminator output does not change appreciably with variations in the receiver output level. This is done primarily in order to bring about smooth enhancement of echoes when the DCG system is used to control the gain of the sound receiver. It is obvious that instability of the system may result if discriminator output is affected by amplitude changes in the receiver output while receiver gain is simultaneously changed by variations in the discriminator output.

4.6 APPLICATIONS OF DCG

4.6.1 QGB (BDI) Equipment

A schematic diagram, illustrating the application of DCG and ODN to equipment utilizing BDI, is given in Figure 22, which shows the circuits employed in the RCA-QGB receiver. The various sections of these circuits will now be discussed in turn.

Limiter Amplifier

The audio input is taken from some point in the sound receiver. The signal level should be at least 6 volts rms when a fairly low output is being obtained from the speaker. The double diode, V-1, is connected as a clipper type of limiter. Current from the B supply flows through R-5, R-3, and R-4; the voltage drops through R-3 and R-4 bias the diodes and prevent clipping until the audio peaks exceed about 4 v. The diode biases are not low enough to prevent some overloading in the amplifier which is the next stage, but once complete limiting is attained, the distortion resulting from overload in the amplifier remains constant and does not affect the circuit as the input level changes. The section including the double triode, V-2, forms a two-stage, cascade, RC-coupled amplifier, the output of which supplies the audio signal to the discriminator transformer, T-101.

Doppler Threshold Adjustment

In the circuit shown in Figure 25, the arm of potentiometer R-22 (point B) is the discriminator output which has the positive voltage slope, and the arm R-23 (point C) is the output having the negative voltage slope. These potentiometers are provided so that the frequencies making the discriminator outputs zero at points B and C may be varied on either side of that frequency necessary to produce zero output at the junction of R-17 and R-16 (point A). Diodes V-5A and V-5B are connected so that only a positive voltage is passed on to the grid of V-6A. The setting of the potentiometer, R-22, is so adjusted that the voltage at point B does not change from negative to positive until the input frequency exceeds that required for ODN zero voltage by an amount corresponding to 1.5 knots of target speed. R-23 is adjusted similarly on the low side of the ODN crossover. When the circuit is properly adjusted, the d-c voltages which appear at points A, B, and C vary with frequency, approximately according to the curves shown in Figure 26. The heavy line of the curves represents the d-c voltage at point D for different signal frequencies. Rectification in diodes V-5A and V-5B allows only the positive portions of the voltages at points B and C to reach point D and the grid of V-6A. As indicated by the curves, only frequencies differing from 800 cycles per second by more than 21 cycles per second produce voltages at D.

Gain Control Amplifier

The amount of gain enhancement developed by a dopplerized signal is a function of the setting of the master gain control. When the master gain control is in the maximum position (minimum positive cathode voltage), the DCG circuits have no effect. On the other hand, when the master gain control is in the minimum position, the plate current of the four i-f tubes produce an IR drop in the control of such magnitude that the steady-state current drawn through V-6B is greatly decreased because of the positive bias put on its cathode. As a result, any further decrease produced in the V-6B plate current by a dopplerized echo must be very

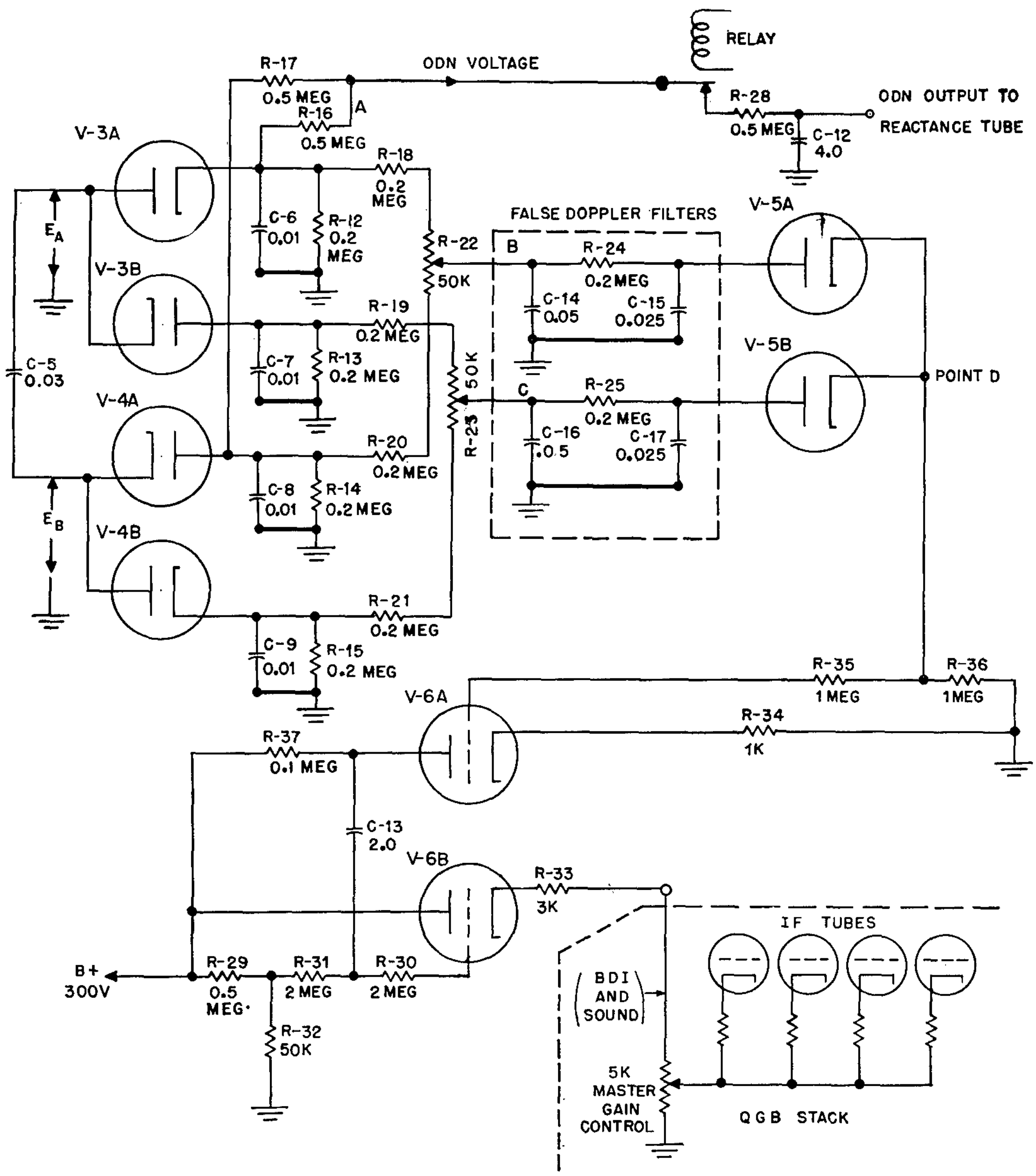


FIGURE 25. Circuit diagram of DCG for RCA-QGB receiver.

low in value. Furthermore, with maximum gain the receiver is usually overloaded—and with minimum gain receiver output is hardly audible; enhancement in either case is unimportant. The point of maximum enhancement is therefore set at about the mid-point of the master control (which is also a good listening level) by adjustment of resistors R-29, R-31, and R-33. The total amount of enhancement is controlled by the value of R-33. Normally, a dopplerized echo which produces complete cutoff of V-6B increases the gain in the sound channel by 6 to 10 db.

FALSE DOPPLER FILTERS

The purpose of the false doppler filters is to prevent operation of the doppler-sensitive circuits during reverberation. When the sonar system is receiving reverberation, the voltages at points *B* and *C* (see Figure 25) have a fluctuating character, the fluctuations being quite

rapid and having peaks of 40 to 60 v. Without some filtering, therefore, signals would reach point D almost continuously, and false enhancements would occur with great frequency.

In the design of these filters it is necessary to

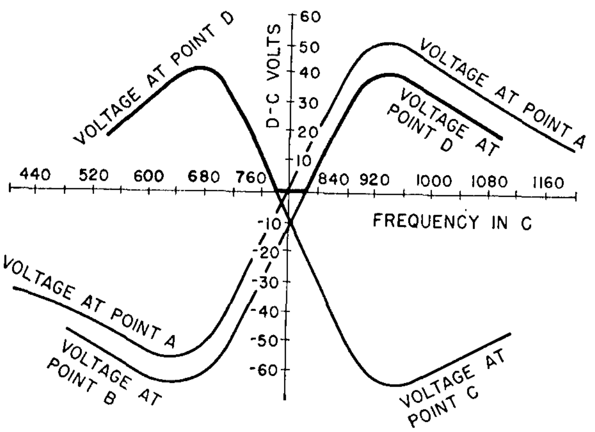


FIGURE 26. Discriminator output curves.

take into account the minimum value of the pulse length, as well as the least amount of doppler required for enhancement. The photographs (Figure 27) of the *target doppler indicator* [TDI] traces illustrate how much greater the reverberation fluctuations are with a ping

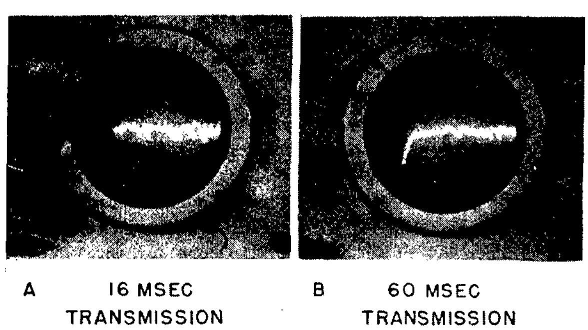


FIGURE 27. Comparative doppler indicator traces.

length of 16 msec than they are with 60 msec. (The TDI circuit includes one section of RC filter.)

The performance of a properly designed false doppler filter must be adequate in the two following respects:

1. The time delay imposed on a true sustained doppler echo should not amount to more than 35 per cent of the pulse length or too much of the echo is lost before enhancement occurs.

2. Reverberation fluctuations in the discriminator output voltage should be too small to send appreciable current through the rectifier tubes V-5A and V-5B.

The two-section filter was selected as a compromise between the greatest acceptable time delay and the minimum number of parts. Somewhat better filtering with the same time delay might be obtained if a filter of more than two sections were used. Rough trials indicated a doppler threshold of 1.3 to 1.4 knots when a four-section filter was adjusted to best performance.

RESULTS OF ENHANCEMENT BY DCG

The results obtained by the application of DCG to BDI are illustrated by the comparative photographs of Figure 23. To obtain these photographs, oscilloscopes were connected in two BDI circuits, one with DCG, the other without. The target used to produce the traces was a stationary echo repeater equipped with an electronic device for injecting an accurately measured synthetic doppler into the echo signal. In order to secure representative traces on the oscilloscopes, the echo intensity was adjusted to be from 3 to 6 db above the reverberation intensity. The photographs show the effect of DCG for both a down-doppler of 2 knots and an up-doppler of 2 knots. On close examination of the comparative photographs it may be seen that the reverberation traces are similar, only the echo traces being enhanced.

4.6.2 Range Recorder

In a submarine, the bearing of a target is usually obtained from target noise. A single ping is then sent out in the direction of the target and its range is determined from the echo trace on a recorder. Since a doppler-sensitive circuit would be controlled only by frequency shift, wrong settings of level controls could not prevent adequate echo traces on a recorder of this type. An extra stylus, fed in the conventional manner from the receiver, could be added

to a doppler-sensitized recorder so that traces for targets without doppler could also be obtained.

4.7 RECOMMENDATIONS FOR FUTURE DCG DEVELOPMENT

As mentioned, DCG, in combination with ODN, has already been accepted for inclusion in QGB and XQHA sonar equipment. In general, its performance is adequate as long as the background against which the echo appears is mostly reverberation. In the case of long-range echoes, however, the background from which the DCG must distinguish the echoes consists of general water noise covering a wide band of frequencies. DCG is not overly successful with these echoes since the doppler-sensitive circuits do not discriminate as well against wide-band noises as against reverberation. This is a fundamental property of the limiter-discriminator system used in the circuits to obtain frequency sensitivity. In submarine installations, this feature is particularly objectionable, since the single ping is likely to be sent out when the target is at long range and is generating considerable noise.

A possible way to overcome this limitation is to employ a type of gate which relies upon sudden gain of amplitude, in addition to doppler-sensitive circuits. In applying this method, the DCG system would utilize an automatic volume expansion circuit to cause an increase of gain in the receiving amplifier whenever the input signal rose suddenly by 3 or 4 db. A possible disadvantage of the scheme is that an echo-to-reverberation ratio higher than that used in the present DCG system might be required.

Mention should be made of a method for applying doppler control of gain which differs substantially from that described here. The functional differences in the two methods can be described best in connection with BDI circuits. In the system described above, the signal in the listening channel, corresponding to an unshifted projector beam, is examined with respect to frequency. If the average frequency as determined by the discriminator response differs from the reference frequency, the gains for both right and left channels of the BDI are simultaneously increased. However, it frequently occurs in practice that the echo from an extended target may involve simultaneous components which differ both in frequency and in direction of arrival. Thus, for a quarter target the sonar projector may be receiving simultaneously a no-doppler wake echo arising from the latter portion of the pulse train, which would produce a left indication, and a down-doppler target echo from the leading edge of the pulse train, which would produce a right indication. If the DCG system is to provide maximum assistance to the operator in resolving such wake and target echoes, the electronic circuits for DCG should be arranged in such a way as to respond preferentially to the dopplerized component of simultaneous signals. In the example described, the DCG should enhance the dopplerized component and yield a proper right indication on the BDI.

Initial study of the problem led to the conclusion that such performance could only be obtained by applying DCG independently to the right and left channels of the BDI system. It is believed that a system for doppler control of directional gain would have important operating advantages and it is recommended that further research be directed toward the achievement of this objective.

Electronic Aural Responder

The electronic aural responder [EAR] is designed to have high discriminatory sensitivity in response to dopplerized signals. The performance of this system is analogous to that of the human ear in its ability to distinguish certain types of signal in the presence of noise which may exceed the signal in intensity. The proposed EAR is capable of responding to pulse signals which are substantially below the level of background noise. For the reception of typical sonar pulses of 30 msec duration, the EAR system seems likely to surpass the discriminatory powers of the human ear by as much as 15 db. Two specific circuits have been proposed, both possessing a feature of automatic adjustment which should make them valuable in the design of recorder systems for single-ping echo ranging from submarines. After further development, this very promising innovation may be applicable to all sonar systems whose operation now requires the exercise of auditory judgments. The EAR was designed by HUSL.

4.8 INTRODUCTION

It is well known that in many cases the human ear can distinguish certain types of signals in the presence of noise which exceeds the signals in intensity. Extensive investigations of related auditory phenomena (at the Bell Telephone Laboratories) finally led to an explanation of this paradox in terms which are both simple and convincing. For the tone or signal to be perceived in the presence of a noise background, it is necessary only that the intensity of the signal equal or exceed the intensity level of the noise within a contiguous critical-frequency band, without regard to the energy which may be distributed elsewhere in the noise spectrum.

This ability of the ear to distinguish signals immersed in background noise, and the audible cues to attention afforded by the pitch sense, have supported the belief that it is impossible to construct apparatus which will provide objective response equaling or exceeding the discriminatory ability of the ear.

This problem is discussed in a series of memoranda[1,2] and it has been pointed out that the ear is able to recognize telegraph-like signals in the presence of interfering noise. In Figure 28, the band-pass filters are given a bandwidth determined by data on masking. This is about 35 cycles per second for reference frequencies in the neighborhood of 800 cycles per second. The low-pass filters preceding the output indicator have a cutoff frequency of about 2.5 cycles per second as determined by the response of the ear to pulses. Thus, for the reception of pulse signals, the ear is closely analogous to a series of telegraph channels having relatively wide filters which admit both signals and interference, and sluggish relays which retard the signal build-up.

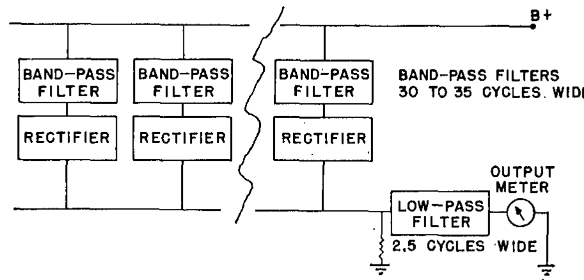
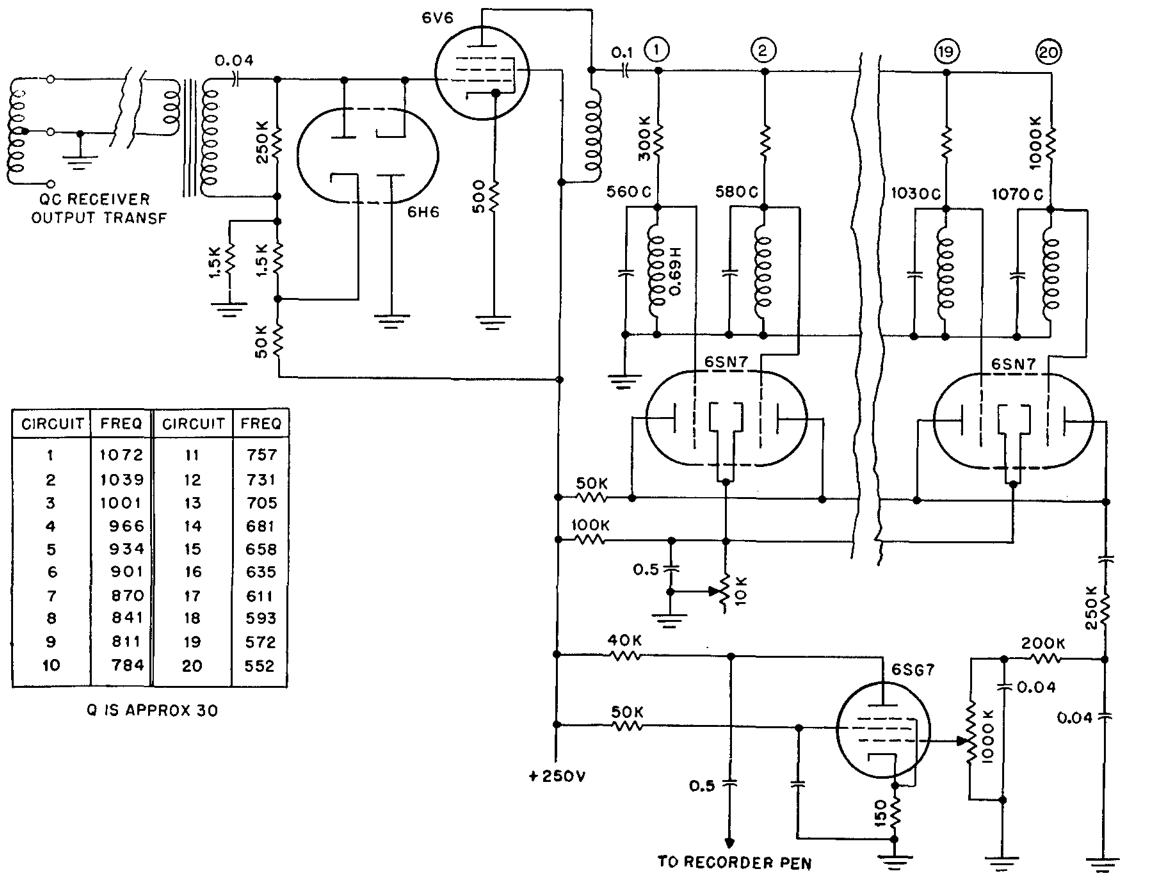


FIGURE 28. Equivalent circuits for human ear response to noise and pulsed signals.

These facts combined with the wartime trend toward the use of shorter pulses in subsurface echo ranging, led to the experiments which finally culminated in the electronic aural responder. This device gives promise of approaching the theoretical performance of ideal systems in the detection of short, weak pulses buried in a masking background of stronger noise and reverberation.

Later consideration of the foregoing work led to the proposal of a related circuit for use in improving the efficacy of the chemical recorder in single-pulse ranging from submarines. In its revised form the proposed circuit seemed to have features which simulated to a remarkable extent the performance characteristics of the human ear. Tests confirmed the general expectations concerning discrimination but revealed that there remained major electronic problems in connection with providing suitable volume control and gating for the individual channels of the system. One of the automatic gate circuits



CIRCUIT	FREQ	CIRCUIT	FREQ
1	1072	11	757
2	1039	12	731
3	1001	13	705
4	966	14	681
5	934	15	658
6	901	16	635
7	870	17	611
8	841	18	593
9	811	19	572
10	784	20	552

FIGURE 29. First proposed circuit for EAR system.

proposed for the EAR system was given a laboratory trial and found to operate satisfactorily.

In view of the success so far attained, and on account of the great value of the prospective results, it is strongly recommended that the principles and circuits of the EAR be made the subject of a thorough investigation. The following pages describe the brief experiments which were carried out, and discuss at some length the proposals for further EAR development.

4.9 DESCRIPTION OF EAR SYSTEM

In studying the behavior of a doppler controlled gain system for use with the chemical range recorder, it appeared that a fundamental limitation in the action of the frequency discriminator circuit was responsible for the fact that desired signals had to exceed interfering noise by about 3 db in order to control discriminator output. A desire to overcome this limitation provided the incentive for experimentation with the first equivalent aural responder [EAR] circuit shown in Figure 29.

The output of the sonar receiver is connected through an input transformer which provides a maximum voltage in excess of 16 v to drive the 6V6 amplifier to full output. A 6H6 limiter is bridged ahead of the 6V6 amplifier in order to limit noise peaks and maintain a fixed voltage level across its output circuit. Twenty individually tuned circuits with *Q*'s of approximately 30, are driven in parallel by the output of the 6V6 amplifier.

The circuit was tested by utilizing the broadband noise produced by operating a standard sonar receiver at high gain with zero input. The i-f selectivity of the receiver was set for sharp and the audio filter switch for flat. With the noise output obtained in this way, a receiver

input signal was adjusted to be 20 db above the noise level but still within the overload limit of the receiver output circuit. The input signal level was then reduced by 27.5 db making its intensity 7.5 db less than that of the broadband noise. Under these conditions, short-pulse signals simulating received echoes produced satisfactory markings of high contrast on the chemical recorder. In comparison with the previous circuit utilized for the enhancement of dopplerized echoes which required a +3-db signal-to-noise ratio for effective operation, the present circuit provided a gain of 10.5 db.

The foregoing experiment was limited to the use of a uniform masking noise spectrum rather than water-borne reverberation and noise. The principal conclusion which could be drawn at this stage of the work was that it is possible to provide reliable recording of desired signals which are at least 7 db below the level of a uniform masking noise spectrum.

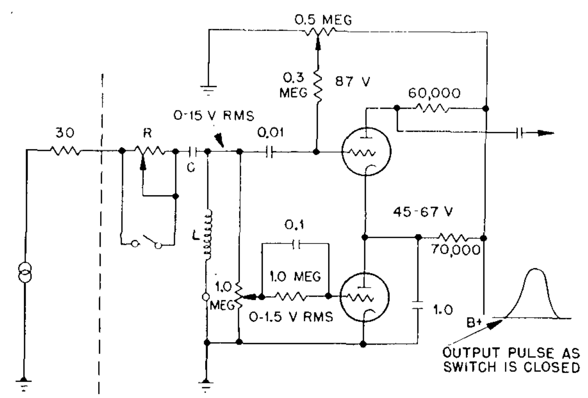
In making adjustments of the circuit diagrammed in Figure 29, it became obvious that better performance could be achieved if the cutoff characteristics of the 6SN7 rectifier were sharper.

4.9.1 Proposed Automatic Gates for EAR

As suggested, the cutoff characteristics of the rectifier in each channel of the EAR system play an important part in determining its performance. Study of the behavior of EAR in the presence of noise or reverberation signals which do not have a uniform "white" spectrum reveals not only that the threshold characteristics of each channel should be adjusted critically, but also that means should be provided for making this adjustment automatically so that each channel may be held at the recording threshold at all times except when a pulse or echo signal is received.

One practical difficulty that arises immediately is the considerable amount of equipment required to provide a good AVC system for 20 audio-frequency channels. This requirement can be substantially reduced by assuming that the sonar system which is to provide signals to the EAR circuits is equipped with *reverberation control of gain* [RCG] so that the major portion of the dynamic range will have been compensated in the circuits ahead of EAR. The function performed by RCG in restricting the dynamic range requirements for EAR could, of course, be provided by a single common AVC circuit applied to the sonar receiver ahead of EAR. This would, however, lessen the usefulness of the sonar receiver for conventional listening purposes since any AVC circuit tends to reduce contrast in signals which follow each other rapidly.

There is an alternative method of approaching the problem of multiple-channel AVC which seems to possess some advantages of conve-



R ADJUSTED TO PROVIDE DESIRED INCREASE IN INPUT WHEN KEY IS CLOSED

FIGURE 30. Automatic gate circuit for EAR.

nience for this application. In the form described above, the AVC in each channel would hold the channel output just below a threshold recording value established in a common combining circuit. This provides the characteristics of an automatic gate circuit which opens to admit signals to the recorder only when the output of one channel momentarily exceeds the common gate threshold.

One circuit which has been proposed for automatic gating of the channels of EAR is shown in Figure 30. A single channel of an automatic gate circuit was set up for preliminary trial of the automatic threshold compensation. The qualitative results indicated that the system is self-compensating over a range of approximately 20 db (see Figure 31). The apparatus complication involved in providing 20 tuned circuits and 20 twin triodes and their associated

resistors and capacitors is not trivial. It may not be too high a price to pay, however, for a discriminatory advantage over the ear which might amount to as much as 15 to 18 db for

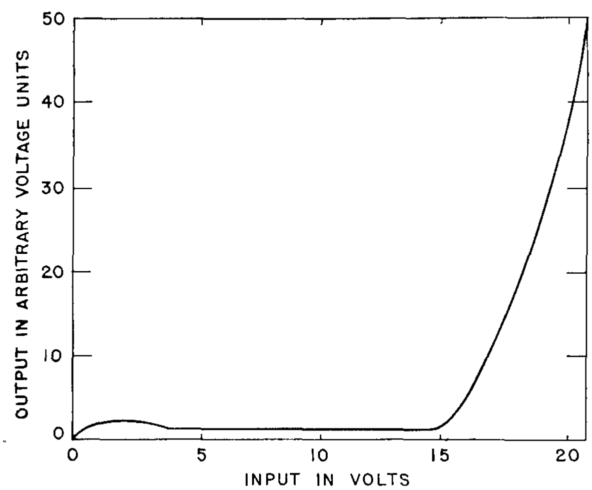


FIGURE 31. Output vs input for automatic gate.

pulse signals of the order of 30-msec duration.

An alternative circuit for achieving results substantially equivalent to those described has been proposed. Although this circuit has not been set up experimentally, it is shown in Figure

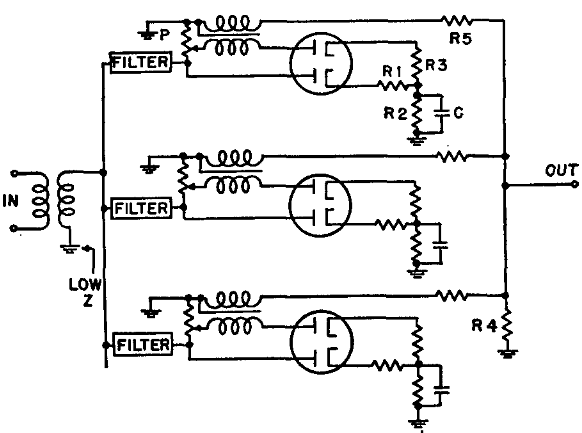


FIGURE 32. Proposed circuit for EAR system.

32 to indicate another of the probably numerous ways in which the functional requirements of automatic gating may be provided for the channels of EAR. In the figure a number of filters are indicated as before, their pass-band width being determined by the pulse length to be received or by the desire to match the masking characteristics of the EAR, and the total number being determined by the total bandwidth to be covered by the recording system.

An interesting characteristic of this circuit is that its output consists of an a-c signal having the same frequency distribution as that selected from the input by the channel filter. Thus it should be possible to connect an amplifier and loudspeaker to the output circuit for conventional listening and for judgments concerning frequency shifts characteristic of doppler effect. Undoubtedly there would be considerable depreciation of tonal quality in such a loudspeaker signal. Whether the elimination of many of the static components of background noise would be of assistance to an operator in making aural judgments must be determined by future experimental trials. But whether the audible output of such an EAR system is useful or not, the circuit appears to be capable of meeting the functional requirements described above for an EAR system for objective recording.

4.10 CONCLUSIONS AND RECOMMENDATIONS

The electronic aural responder system which has been proposed appears to provide a system of tolerable complexity capable of recording objectively pulse signals which are substantially below the level of noise or reverberation. For the reception of pulses of the order of 30 msec duration, the EAR system seems likely to surpass the discriminatory power of the human ear by as much as 15 db. Two specific circuits which have been described possess the feature of automatic adjustment, which should make them valuable in the design of recorder systems for single-ping echo ranging from submarines. On the basis of the inherent potentialities of these circuits or their functional equivalents, it is strongly recommended that further experimental work be prosecuted to the point of determining the applicability of these principles to all sonar systems whose operation now requires the exercise of auditory judgments.

Reverberation Suppression Filter

The reverberation suppression filter [RSF] is a sharply tuned rejection filter which has maximum attenuation at the audio frequency (usually 800 cycles per second) to which incoming reverberation is heterodyned by a local oscillator operating under own-doppler nullifier control. By suppressing the level of the reverberation signals, greater contrast of echo signals having doppler shift may be realized, particularly at short ranges. Using a multisection bridged-T null-type filter, the RSF can offer a 40-db discrimination against signals 10 cycles per second above or below an 800-cycle-per-second center frequency. The reverberation suppression filter was developed by HUSL.

4.11 INTRODUCTION

The amplification which may be employed in a sonar receiver is dependent to some extent on the reverberation intensity incident on the transducer immediately after the transmission of a ping. Unless the gain of the receiver is restricted, the initial amplitude and reverberation causes overloading.

One method of limiting the amplifier response is to apply *reverberation controlled gain* [RCG]. An RCG unit automatically adjusts the gain in accordance with the volume and the persistence of reverberation. This method of control, however, is not always sufficient to produce the most desirable signal-to-noise ratio. An ODN unit is therefore assumed to be used in conjunction with the reverberation suppression filter.

The RSF was conceived to reduce the response to echoes from stationary objects, and to permit the echoes from moving targets to be received without appreciable diminution in intensity. The RSF unit achieves this by passing the incoming signals through a filter which produces high attenuation of undopplerized echoes, heterodyned to 800 cycles per second, but little attenuation of beat frequencies immediately above and below 800 cycles per second. After numerous attempts to design a filter with these characteristics, the bridged-T

FIGURE 33. RSF assembly with air coils.

null type[3] of filter was found to offer the greatest promise.

The results obtained with the early experimental model of the modified multisection bridged-T null-type filter clearly indicated that such a filter has useful possibilities as a reverberation suppression device. The later tests, in which only a single section of the bridged-T filter was used, were inconclusive with respect to RSF itself, since its characteristics were greatly compromised to meet space limitations. It is felt that the fundamental principle of the RSF has sufficient merit to justify further development.

4.12 DESCRIPTION OF REVERBERATION SUPPRESSION FILTERS

The performance of the ideal filter for reverberation suppression is pictured by the graph in Figure 34. In this filter, the narrow band of frequencies extending 10 cycles per second on each side of the heterodyned audio frequency of 800 cycles per second is attenuated by an arbitrary and adjustable amount with respect to neighboring signals. Large attenuation is also provided for signals lying outside the frequency range required to include the maximum target doppler shift likely to be encountered.

Various circuits were tested and abandoned because of instability and too critical adjustments. Because of its desirable properties, a bridged-T null-type filter was adopted (see Figure 35). The characteristics of this type of filter are shown by the graphs in Figure 36. The effect of the Q of the coil is apparent in the relative spreading of the rejection band with

increasing differences. Large air-core coils were tried but were found to be too sensitive and this caused erratic filter performance.

4.12.1 Performance of RSF

RSF AND COMPUTED-CORRECTION ODN

In early tests of the first reverberation suppression filter, strict precautions were taken against magnetic disturbances. The ODN in use

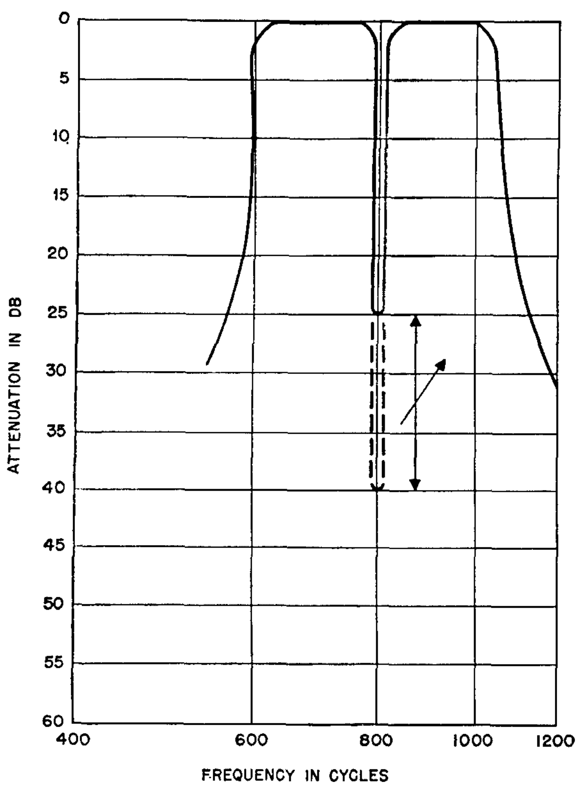


FIGURE 34. Ideal characteristics of reverberation suppression filter.

at this time was of the computed-correction type. From observations of the results it was concluded that the filter performed as expected in providing enhancement of dopplerized echoes but that high-Q coils of limited magnetic fields were definitely necessary. Further difficulties were encountered with the ODN and RSF combination when the ship was in motion. It was found impossible to maintain the center frequency with sufficient accuracy either manually or by means of the ODN, which was provided with a hand setting to correct for ship's speed. It seemed likely, moreover, that the changes in the components with time, temperature, and weather would further mismatch the center frequencies of the ODN and the RSF.

RSF AND ELECTRONIC ODN

The advent of the electronic ODN with a frequency discriminator in its circuit made it pos-

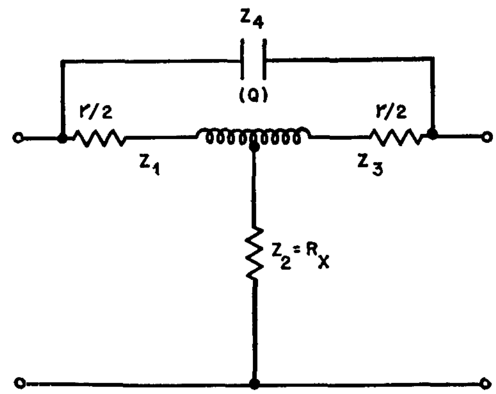


FIGURE 35. Bridged-T null-type filter.

sible to introduce the RSF in such a manner that it controlled the center frequency and also increased the overall sensitivity of the ODN. A schematic diagram of the combination is

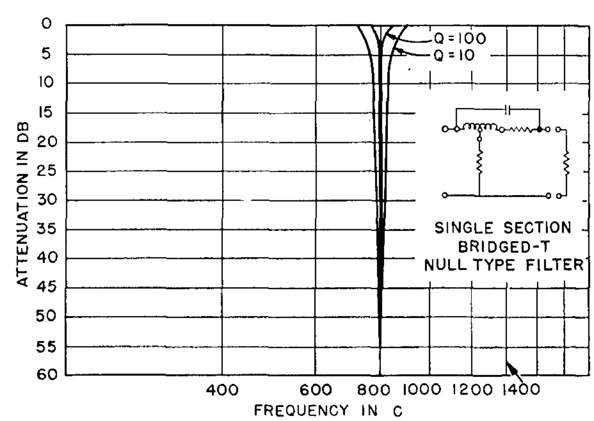


FIGURE 36. Characteristics of single section, bridged-T null-type filter. Effect of Q.

shown in Figure 37. A more detailed description of the operation of this circuit, called the Brooks-Sebring discriminator, is given in Section 4.2.3. Only the interaction between the ODN and RSF devices will be discussed here.

Transformer T-1 is tuned to 800 cycles per second. If the condenser C-3 is connected as shown by the dotted lines, the system is equivalent to a Foster-Seeley discriminator. The C-3 condenser then supplies a zero-degree phase reference for the secondary of the transformer so that the two terminals of the secondary lead and lag by 90 degrees respectively.

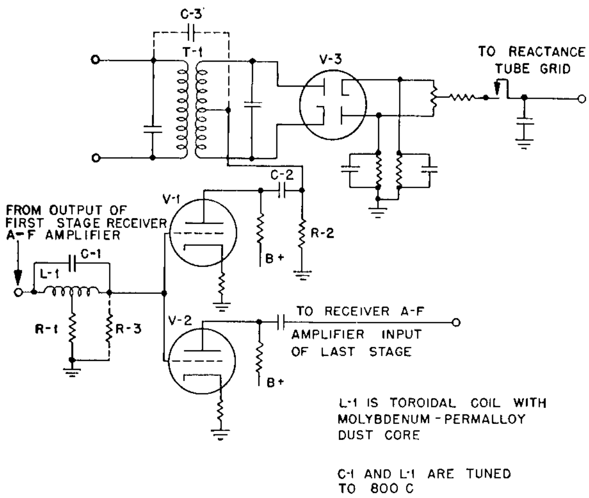


FIGURE 37. Schematic diagram of ODN and RSF combination.

With the zero-degree phase reference supplied by the RSF, the latter is also tuned to 800 cycles per second, the frequency of maximum attenuation for the filter. At this frequency, the detector will have substantially zero output. Around 800 cycles per second, the amplitude and the phase angle in the RSF output change rapidly with small changes in the frequency of the input, the rate of change being much greater than in the Foster-Seeley circuit. The result is that the RSF becomes, in effect, the discriminator for frequencies near the center frequency and materially increases the sensitivity at this point.

A modified RSF system was included in the combined unit known as the *echo ranging booster* [ERB] with provision being made for the RSF to be switched in or out of the receiver and audio system. The main difficulty found in the ODN and RSF combination assembled in the ERB unit was the sharpness of the filter notch at the center frequency. This imposed an almost impossible accuracy requirement on the ODN, which was never fully met by the equipment. The RSF action was particularly noticeable when the ODN center frequency coincided with the center of the RSF notch. When the center frequencies were not correctly adjusted, the RSF effect was not so pronounced and undesirable results were obtained. For ideal RSF performance the characteristics achieved with the multisection filter are a necessity.

4.13 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

The use of a multisection bridged-T null-type filter presents the possibility of securing an amplitude discrimination of as much as 40 db for alternating currents differing as little as ± 10 cycles per second from a center frequency of 800 cycles per second.

The three major requisites visualized in developing a successful RSF application are the following:

1. An adequate ODN device to provide an automatic and accurate adjustment of the sonar receiver so that the transmitted supersonic frequency is heterodyned to a predetermined audio frequency regardless of the motion of the transmitting vessel and the direction in which the projector is pointed.
2. An RSF filter design which will provide a high value of attenuation of the predetermined audio frequency, and an attenuation band sufficiently wide to allow the ODN to function properly.
3. The introduction of such an RSF filter into the ODN circuit so that the RSF will control the center frequency.

The present RSF, it appears, will be adequate to achieve the purposes outlined above if the filter notch is sufficiently widened to make certain that the center frequency will fall within it, and if the ODN discriminator response is broadened to insure a greater reliability than is achieved at present. The widening of the filter notch may be accomplished by using additional sections of the bridged-T null-type filter. Suitable band-pass filtering may also be introduced to secure the desired filter characteristics. If the first section of the RSF, tuned to the center

frequency, is used to control the ODN and if the other RSF sections, after the isolating tube, are used to modify the characteristics appropriately, the three requirements listed above will be satisfied.

Finally, it appears that suppression of undopplerized signals might satisfy the direction-discriminating needs of BDI channels, referred to in Section 4.8. It is suggested, therefore, that the possibilities of RSF in this application be given consideration whenever investigation of this problem is undertaken.

Target Doppler Indicator

The target doppler indicator [TDI] is auxiliary sonar equipment designed primarily to indicate range rate by determining the amount of doppler shift in the frequency of the echo. The unit consists of a frequency discriminator the output of which is applied to a cathode-ray oscilloscope screen, calibrated to read in knots. In the laboratory, the TDI also served a useful purpose in enabling quantitative study of doppler nullification and enhancement circuits (ODN and ADE) and in measuring the effectiveness of false doppler filters for the doppler controlled gain [DCG] equipment. Although sea tests of the latest TDI model to be constructed showed satisfactory results, the device was not adopted by the Navy for Service equipment because it appeared that the cost of the auxiliary function in terms of bulk and complexity of apparatus was excessive. This difficulty might be surmounted by incorporating the TDI with the ODN unit. The target doppler indicator was developed by the Harvard Underwater Sound Laboratory.

4.14 INTRODUCTION

The story of the development of the *target doppler indicator* [TDI] is one of early frustration followed by success which came too late and at too great a cost for Service adoption. All the early work was directed toward providing a meter indication of the doppler frequency shift arising from radial motion of the target in approach or recession. As is pointed out below, an indicating meter can furnish to the operator only a single numerical quantity; its success as a target doppler indicator is predicated on the false assumption that the echo signals are of such a character as to admit of simple numerical description. Various TDI circuits were studied in conjunction with development work on ODN and *audible doppler enhancement* [ADE] devices and finally, as a result of the improved performance of electronic ODN circuits, a TDI chassis labeled Model I was constructed. Its performance was seriously hampered by the effects of reverberation and noise. In an attempt to improve its erratic behavior, the system was coupled to a range gate which connected the TDI to the receiver only during

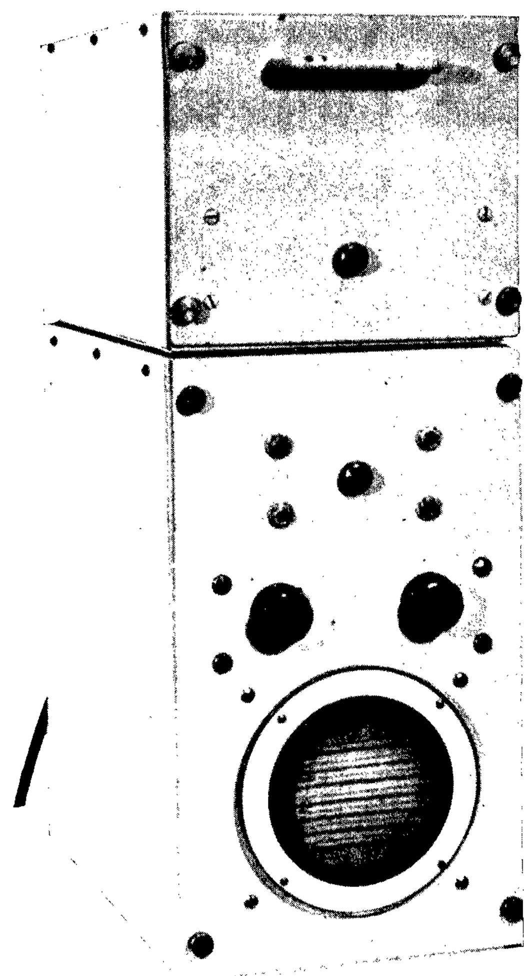


FIGURE 38. Chassis of TDI-CRO model.

the gated echo interval. The gate was provided first in mechanical form; later an automatic range gate as employed in *automatic target training* [ATT] (see Section 3.2) improved performance considerably, but the fact that it could be used only when ATT was in operation provided a serious handicap. Moreover, the TDI was still affected by reverberation or noise appearing with the echo signal during the gated interval. With results still far from satisfactory, the TDI project was temporarily abandoned. Further development of ODN and DCG created need for a device to measure target doppler and the TDI project was accordingly revived. Since experience had been acquired with the frequency discriminator circuits employed in ODN and DCG, it was decided to construct a TDI using a *cathode-ray oscilloscope* [CRO] to provide quantitative indication of the output of a frequency discriminator. This unit, known as the TDI-CRO model, was almost immediately successful, and was used in making quantitative measurements on DCG circuits and in connection with performance studies of dopplerized echo repeaters.

4.15 DESCRIPTION AND PERFORMANCE OF TDI CIRCUITS

4.15.1 Model I TDI

Description

Figure 39 is the block diagram of the TDI circuit which was identified as Model I. The schematic diagram is given in Figure 40.

The first requirement of such a TDI system is that it translate the frequency shifts of dopplerized echoes into electrical amplitude variations which can be indicated on a meter. In the Model I TDI this task is accomplished by a limiter-discriminator system of the type normally used for demodulation in f-m radio receivers.

It is further desirable that the indication of a dopplerized signal be the only reading registered and that this reading remain continuously on the meter between pings. This requirement is taken care of by using a range gate.

It may be seen in the circuit of Figure 40 that considerable precautions are taken to insure that the limiter output retains a symmetrical square wave for all reasonable inputs. Also noteworthy is the elaborate band-pass filter between the last two amplifier stages. This filter is included to provide the discriminator with a sinusoidal input regardless of the signal intensity. The discriminator circuit used in this TDI is found to be somewhat sensitive to the wave form of the input.

Performance

When the Model I TDI was tested, its overall performance as an indicator was unsatisfactory; first, because its circuits depend on the operation of the ATT range gate, and second, because of inaccuracy and drift in the metering circuit.

A number of other meter circuits were tried subsequently, but all were subject to the same disadvantage of indicating the difference between the intensity of the echo signal and that of the random noise with opposing polarity, and all yielded disappointing results. It is now evident that these early failures resulted from the lack of recognition of the following factors.

1. The a-c voltage peaks at the output of a discriminator circuit fed with reverberation have magnitudes corresponding to fluctuating frequency shifts of 5 to 6 knots at 20 kc for a 50-msec pulse.
2. The peaks arising from reverberation, however, rarely persist for more than a few milliseconds, whereas the doppler shift of a true echo lasts for the full length of the pulse.

The solution of the problem consists, therefore, in providing filter circuits which strongly attenuate short pulses but pass the later portions of long pulses.

4.15.2 The TDI-CRO Model

Description

The circuit of the TDI-CRO model (Figure 42) consists of the conventional components, a limiter, an amplifier, a band-pass filter, and a discriminator, the output of which is connected to a cathode-ray oscilloscope. The oscilloscope screen is calibrated to read from —3 knots,

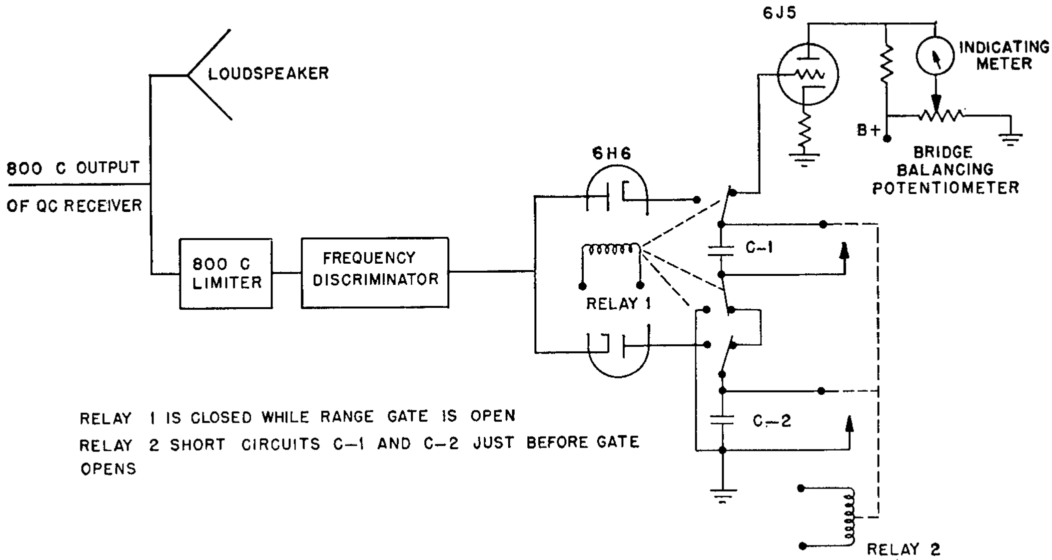


FIGURE 39. Block diagram of Model I TDI.

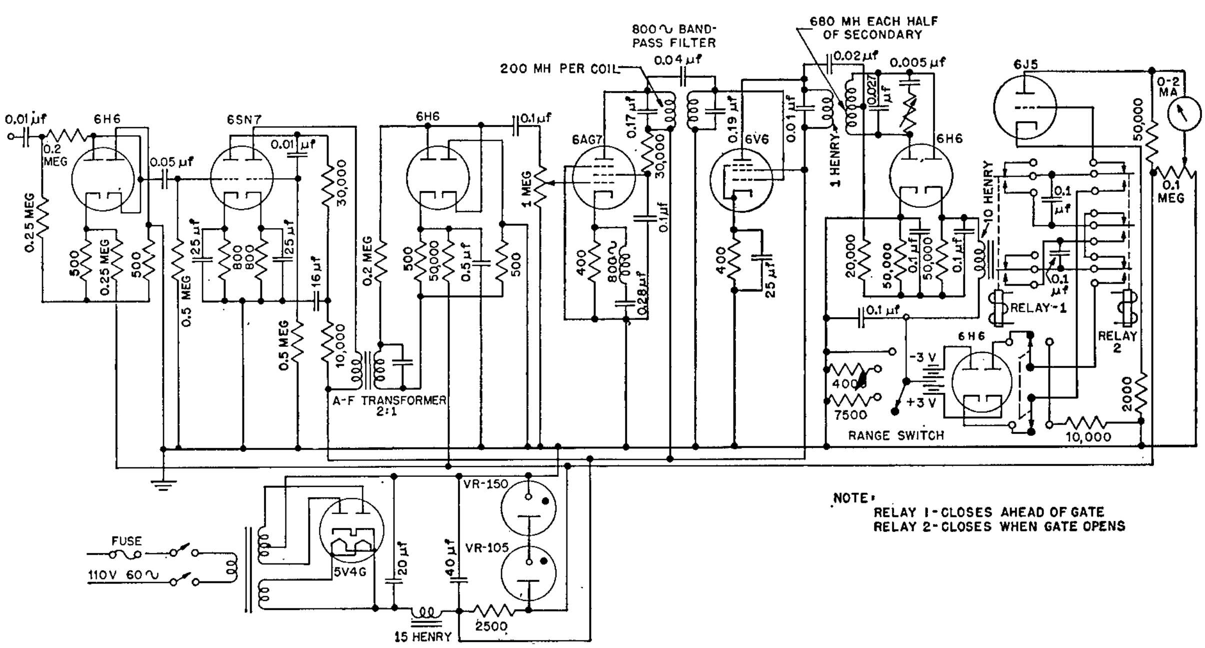


FIGURE 40. Schematic diagram of Model I TDI.

down-doppler, to +3 knots, up-doppler, in steps of 1 knot.

Applications

This model of the TDI is useful in measuring the effectiveness of false doppler filters for DCG. In testing a filter, it is inserted in the TDI circuit between the discriminator output and the input to the oscilloscope amplifiers. By study of the resulting trace an evaluation of filter performance is readily obtained. All pips appearing on the screen (except target pips) which exceed a deflection of 1.6 knots are false dopplers, that is, cause false DCG operation. Figure 43 is a sketch showing the typical appearance of reverberation and echo traces on the TDI screen.

Other uses for the model include studies of minimum pulse length, calibration checking of the dopplerized echo repeater, evaluation of the stability of an ODN, and investigations of unusual frequency changes in reverberation. The traces observed provide good pictures of the random nature of reverberation, and the effect upon it of variations in length of modulation of the transmitted pulse.

In sea tests of this TDI-CRO model, both submarines and dopplerized echo repeaters were used as targets. In both cases satisfactory results were obtained.

4.16 CONCLUSIONS AND RECOMMENDATIONS

The goal of providing equipment to yield an objective and quantitative indication of target doppler appears to have been achieved in the

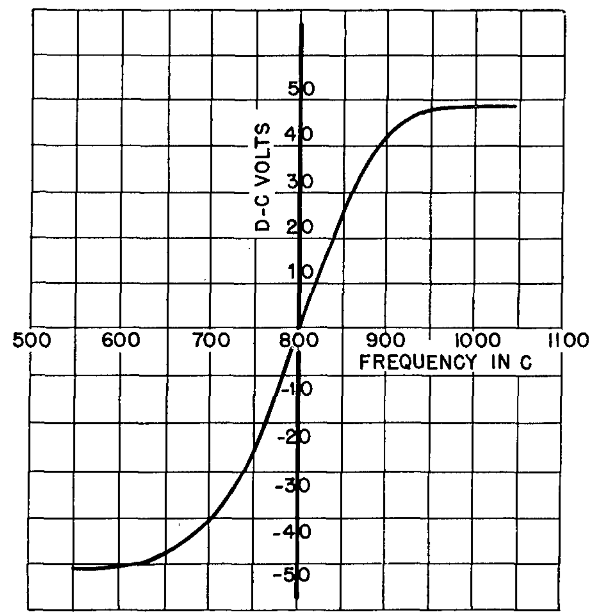


FIGURE 41. Discriminator characteristics of Model I TDI.

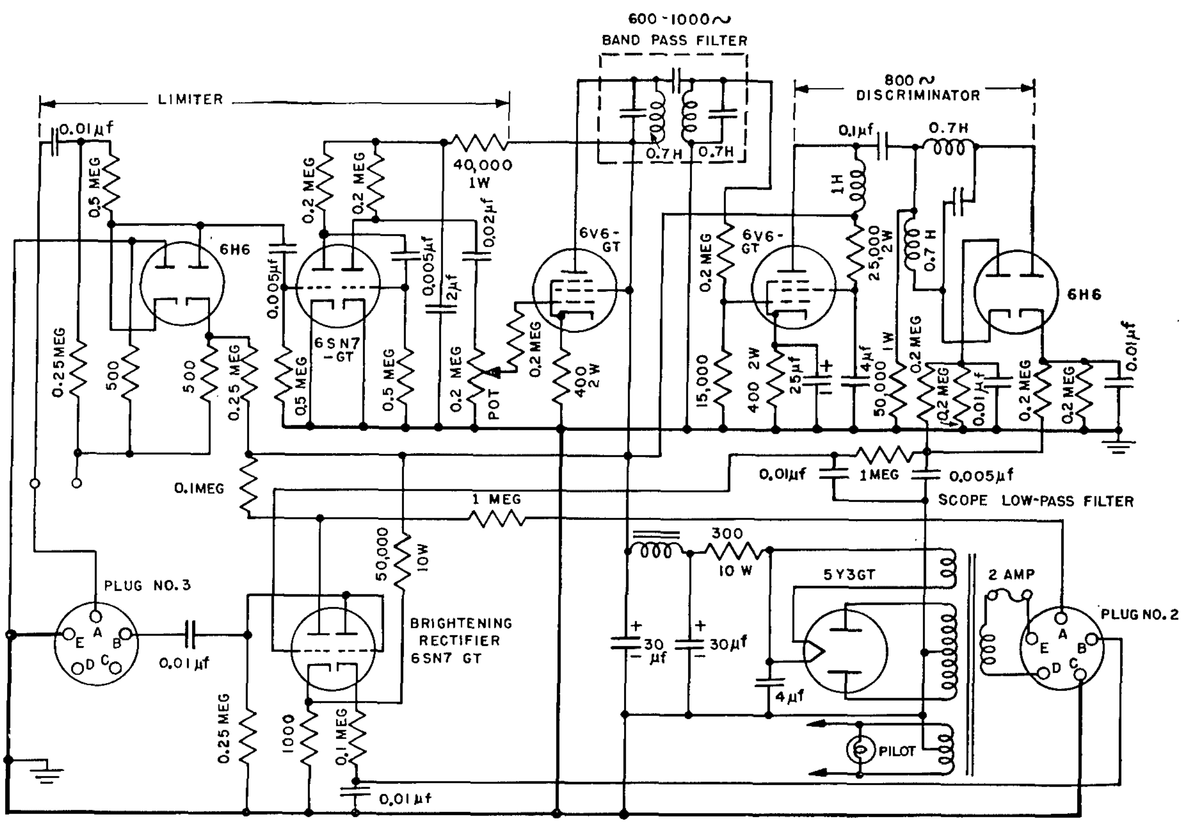


FIGURE 42. Schematic diagram of TDI-CRO model.

CRO-TDI. This unit served a useful purpose in providing for quantitative study of doppler nullification and enhancement circuits. The device was not adopted by the Navy for Service equipment because it appeared that the price of the auxiliary function in terms of bulk and complexity of apparatus was excessive. This objection might be removed in considerable part by an integrated design of a target doppler indicator operating in conjunction with an own-doppler nullifier circuit. Presumably, target doppler indication could be achieved by arranging a suitable cathode-ray indicator to delineate the signals delivered by the ODN discriminator's unfiltered output. If other forms of modern sonar equipment, such as scanning sonar, appear still to involve reliance upon an operator's auditory discrimination for detection of early target maneuvers through interpretation of doppler shift, it would appear worth while to devote additional engineering development time to the design of simplified equipment for yielding TDI.

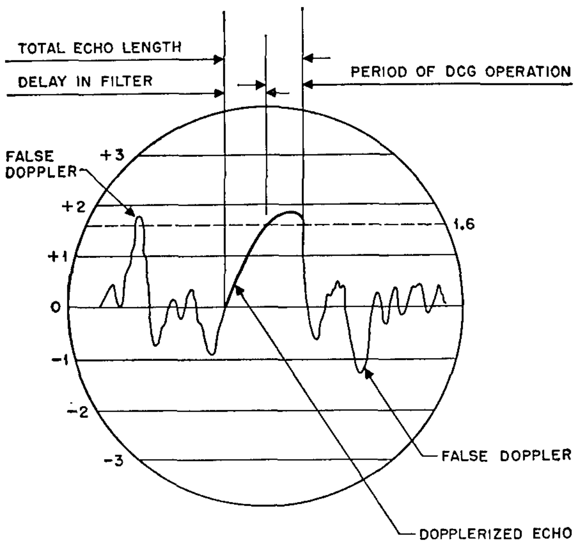


FIGURE 43. Sketch of reverberation and echo traces on TDI screen.

If further development of a meter type of TDI should seem desirable, the doppler-sensitive circuit diagrammed in Figure 44 is proposed as a possible solution of the problem.

The meter portion of this circuit contains two meters, one for up-doppler and one for down-doppler. Two meters are used to prevent a reading of an up-doppler from being disturbed by a succeeding down-doppler or vice-versa. Once a doppler echo has been indicated, the only event which can affect the reading is another echo having a larger doppler of the same sign.

In spite of the apparent simplicity of meter indication, however, the basic phenomena are not simple. Moreover, in conjunction with integrated designs including the ODN function, the cathode-ray presentation of target doppler ap-

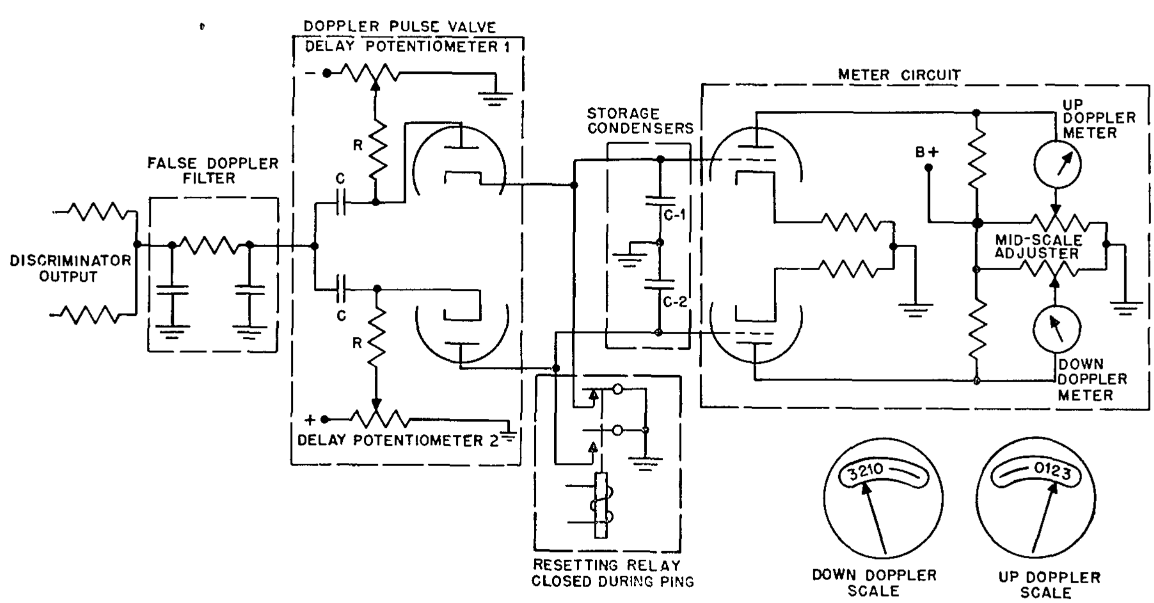


FIGURE 44. Proposed TDI circuit.

pears to offer the greatest economy in equipment. In practice, therefore, utilization of the latter method and provision of the requisite operator training in interpretation of the resulting doppler patterns, would probably be the most satisfactory procedure.

Echo Doppler Indicator

The echo doppler indicator [EDI] is an auxiliary sonar unit designed to (1) differentiate between the pitch of the transmitted ping and the subsequent echo, and (2) compare the echo with the reverberation frequency. When the EDI is connected to the audio-frequency output of any echo-ranging gear, the reed of a vibrating-reed frequency meter having a period of vibration most nearly equal to the echo frequency will vibrate with the greatest amplitude. Thus the operator can detect the amount of doppler shift with quantitative accuracy not possible with aural detection. The EDI was developed by Columbia University, Division of War Research, New London Laboratory, Fort Trumbull, New London, Connecticut.

4.17 INTRODUCTION

Because of its relation to movements of the echoing and target vessels, doppler effect provides valuable information in subsurface warfare. The echo doppler indicator, essentially a frequency meter with vibrating reeds, is intended for visual measurement of these frequencies. The EDI supplements aural devices now in use; it does not displace them. As an instrument for determining the exact amount of doppler more reliably and more easily, EDI is an aid in correct evaluation of all shifts. As a meter for the true amount of frequency shift between transmission and echo, it indicates range rate. It provides a direct measure of the amount of motion along the projector bearing (up- and down-doppler) by indicating the difference between shifts introduced from targets into the echo and into the reverberation.

When connected to the audio-frequency output of any echo-ranging gear, the EDI indicates doppler effect by means of a vibrating-reed frequency meter, modified for high-frequency sounds. Mounted between the poles of a C-shaped permanent magnet and surrounded by a driving coil, the reeds respond to all frequencies within their band. Thus they indicate frequency changes. Since the amount of echo

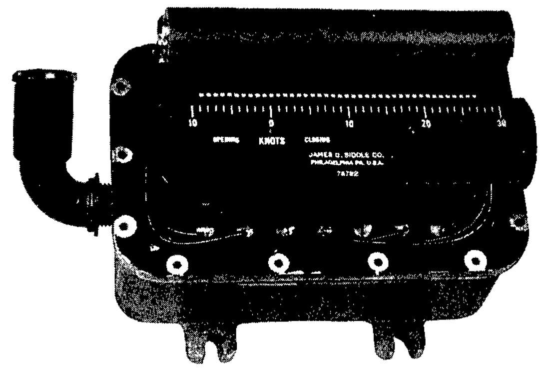


FIGURE 45. Model 2 of EDI showing indicator scale capable of responding to opening and closing range rate.

frequency change from a target is directly proportional to the range rate, the scale on the meter indicates knots range rate. The entire equipment consists of the vibrating-reed frequency meter and an amplifier unit located between the ranging gear and the indicator.

Although the ear is capable of detecting small changes in pitch often more rapidly than the EDI, the EDI can accurately evaluate all pitch increments. It has performed so effectively that it is possible, from a single echo-ranging ping, to determine range rate to an accuracy of 1 knot or better. In addition to simplifying present echo-ranging operation, the EDI may be of considerable value in further detailed study of doppler effect phenomena.

4.17.1 Description of EDI Operation

In echo ranging, the frequency of the returned echo often differs from the frequency of the transmitted wave. This is doppler effect. General reverberation doppler results from the reflection of the transmitted wave by the sea

bottom, the shore, the water itself, or other reflectors. The amount of frequency shift is proportional to the rate the echoing vessel is moving along the line of bearing of the projector. An echo from a target vessel shows a different frequency shift; this is due to relative movement of the two vessels and is proportional to the speed with which the two vessels are approaching, or receding from, each other. Thus it is directly proportional to the range rate.

Echo-ranging equipment heterodynes the supersonic wave received to produce an audible tone of a definite frequency. For any given amount of frequency change in the supersonic signal, there is a frequency change in the audible tone of exactly the same number of cycles per second. The action of the heterodyning circuits, therefore, greatly increases the percentage change in frequency due to the doppler effect. Nonetheless, the resulting pitch differences remain too small to be readily evaluated by the normal listener. The EDI provides an easier and more quantitative means of identifying the shift.

During the early portion of a pinging cycle, a number of indicator reeds respond to reverberation (Figure 46) more or less simultaneously because the transmitted beam has considerable breadth. The center reed of the group usually indicates the speed of the ship's forward motion, multiplied by the cosine of the projector's relative bearing angle; adjacent reeds indicate the same speed multiplied by the cosine of relative bearings other than that of the projector's true axis but still within the beam. At the instant an echo is received from a real target there will be a distinct response of one or, at most, two reeds. If the responding reed is within the group responding to reverberation, the target vessel is not moving along the line of the projector bearing. If the echo indication appears above the group responding to reverberation, the target vessel is approaching the echoing vessel along the line of bearing; if the echo indication appears below the reverberation indication, the target is moving away from the echoing vessel along the line of bearing. These two indications are up- and down-doppler. However, the range rate may be closing in both cases. With up-doppler indication, the range rate is closing more quickly than the speed of the attacking vessel along its line of bearing; with down-doppler to the contrary. Down-doppler does not, therefore, necessarily indicate an opening range rate. It merely shows that the target vessel is moving away from the attacking vessel at a speed less than the speed of the latter.

Because both opening and closing indications are sought, the scale, read directly in knots, indicates a range rate of from —10 (opening) to +30 (closing) knots, as shown in Figure 45.

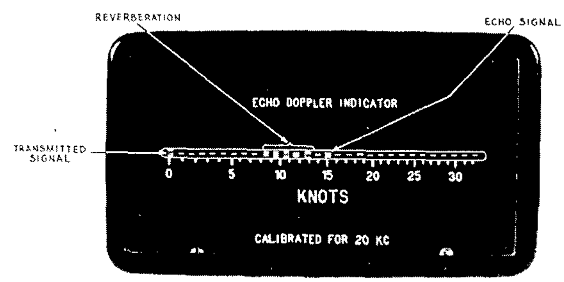


FIGURE 46. Model 1 of EDI showing reeds vibrating to reverberation and echo signals.

Operating on a frequency band of 650 to 1,280 cycles per second, the EDI can be used interchangeably with echo-ranging equipment operating on 20 or 24 kc. If other transmitting frequencies are used, a correction factor must be considered to obtain true range rate.

Since the calibration of the EDI is based on the amount of frequency change the doppler introduces into the received signal, it is valueless when used in conjunction with doppler nullifiers or doppler enhancers.

4.17.2 Principles of Operation

Since the only connection required is a tap across the a-f output of the echo-ranging receiver, the EDI may be connected to any type of echo-ranging gear. After amplification, the echo signal is applied to the coil surrounding the frequency meter reeds. A rectified power supply provides a circuit voltage of about 475 v (see Figure 47).

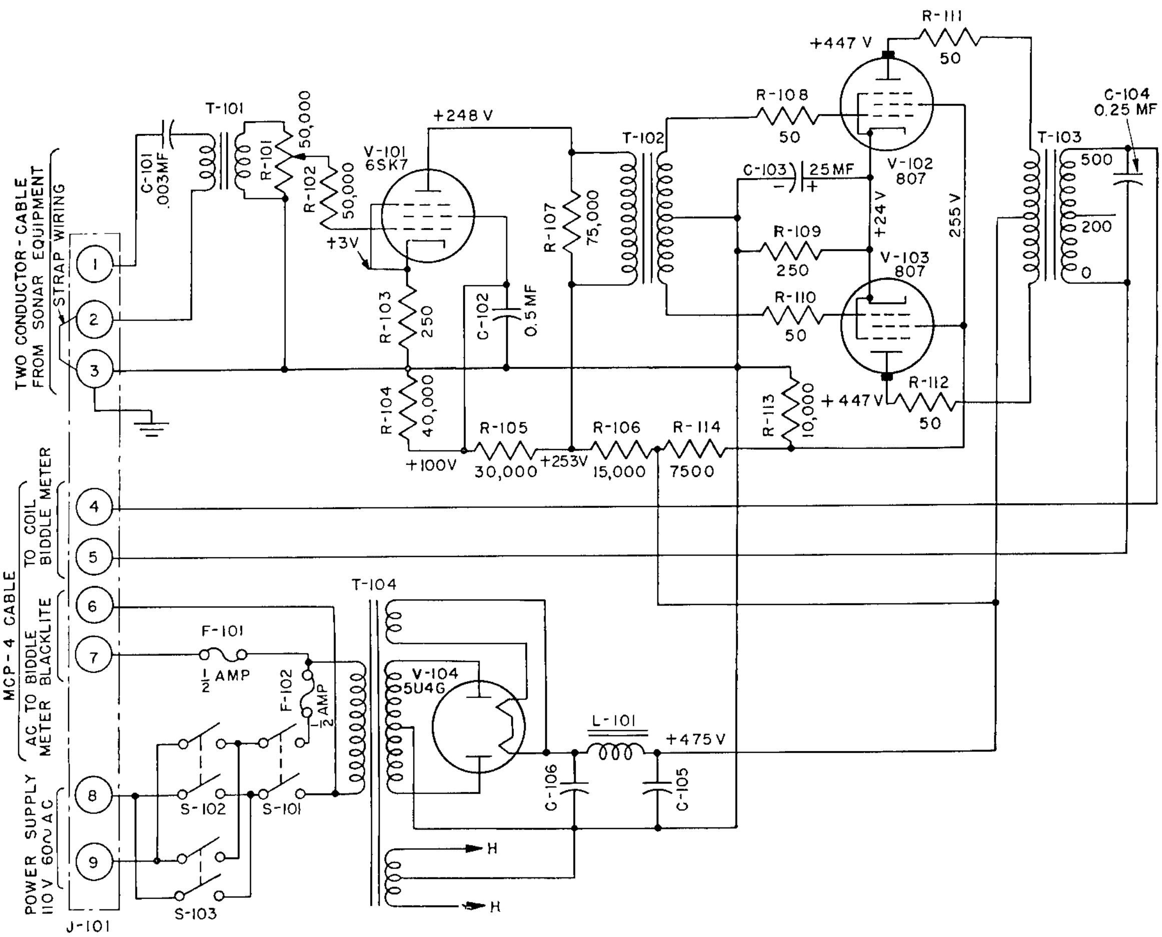


FIGURE 47. Circuit diagram for echo doppler indicator.

The Amplifier Unit

Transformer-coupled (T-101) to the echo-ranging receiver output, the amplifier unit consists of a two-stage audio-frequency amplifier. A high-impedance input is applied across the grid and cathode of the first stage, a 6SK7 pentode amplifier (V-101). A volume-control R-101 regulates the supply to the grid of the tube. The first stage is transformer-coupled (T-102) to two 807 tubes (V-102 and V-103) operating in push-pull. This stage is transformer-coupled (T-103) to the coil of the frequency meter. The unit is designed to amplify frequencies between 600 and 1,300 cycles per second, producing uniform indications throughout its frequency range.

Power Supply

The power supply consists of a 5U4G high-vacuum half-wave rectifier tube and a condenser-input filter, and provides the 475-v plate supply for the amplifier unit.

Indicator Unit

Forty-one reeds with resonant frequencies varying from 650 to 1,280 cycles per second are mounted in a row at the magnetically neutral line midway between the poles of a long C-shaped permanent magnet. A coil across the output of the amplifier unit carries alternating current within the frequency range of the indicator. When the coil is energized, the reeds will be attracted alternately to the poles. The

reed having a natural period of vibration most nearly equal to the echo frequency will vibrate with the greatest amplitude.

4.18 PERFORMANCE AND CRITICISM OF EQUIPMENT

By observing response of the EDI during echo-ranging frequency variations, the operator can detect the amount of doppler shift with quantitative accuracy not possible with aural detection.

Changes in instrument design were instituted after completion of the first model. A more versatile instrument resulted from (1) use of two alternative scales, one for 20-kc and one for 24-kc pinging frequencies, and (2) extension of the scale to include opening as well as closing range rate. The initial instrument, constructed for only 20-kc pinging frequency, read directly in terms of negative (closing) range rate from 0 to 32 knots. Making the reeds longer, heavier, and stiffer, and providing them with more adequate bumpers, mechanically strengthened the instrument. An increase in air-gap spacing increased magnetic reluctance between the reed and the "neutral point" of the permanent magnet, thus providing insulation for the a-c flux.

Aside from repair and calibration of echo doppler indicators, no active development work has been done on this project since June 1944. Tests have shown that the instrument performs satisfactorily.

Audible Doppler Enhancer

The audible doppler enhancer [ADE] is an electronic device which enhances the frequency shift of dopplerized echoes. In all the circuits for frequency multiplication which were studied, the improvement in doppler recognition led to so serious a degradation of tone quality as to make the doppler enhancement undesirable from an operational point of view. However, a promising method has been suggested which would avoid the difficulties of tone depreciation in circuits of this type. The development of the various ADE devices was carried on independently by the West Coast Sonar School in collaboration with the staff of the UCDWR laboratory at San Diego, California, and by HUSL.

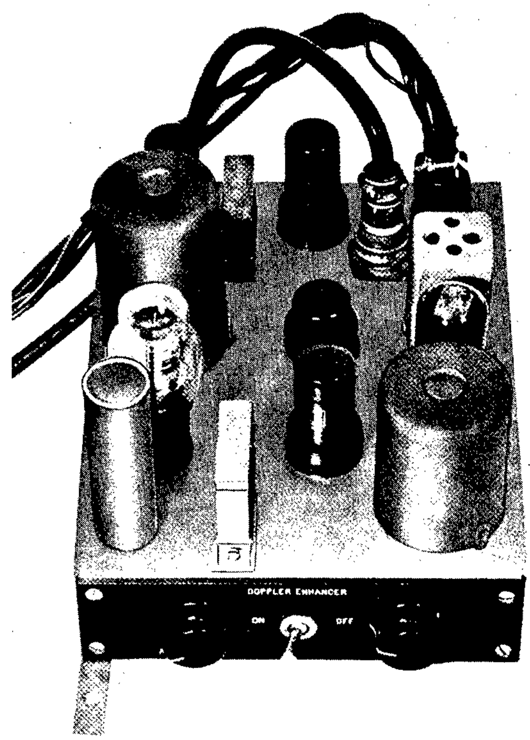


FIGURE 48. Chassis of second ADE model.

4.19 INTRODUCTION

Increased detectability of the doppler frequency shift of echoes reflected from a moving target is the purpose of the electronic devices classified as audible doppler enhancers. These devices employ various methods for enhancing doppler, but in general, each one multiplies an incoming frequency by a small integral number, filters the result and then, if necessary, heterodynes it again to the desired output frequency. This procedure may be applied either to an audio output frequency or to an intermediate frequency, but filtering is much easier in the latter case.

There are three major requirements which must be met by a satisfactory ADE circuit: (1) the doppler of an echo shall be multiplied by a factor (greater than 1), which is independent

of the magnitude of the frequency shift and of the signal level; (2) if two signals of comparable amplitudes are introduced, the outputs must consist only of the two multiples of the input frequencies with no other frequencies present such as might result from cross modulation; and (3) the signal-to-noise ratio shall not be decreased by the ADE.

None of the ADE circuits assembled met all of these specifications and their study led to some presumption that the specifications cannot all be satisfied simultaneously. This negative conclusion seems to be sound, at least for that equipment described below. Attention is directed, however, to the linear systems exemplified by the fifth ADE discussed, and to certain schemes for frequency multiplication involving television scanning techniques which have received the consideration of the San Diego laboratory in connection with a problem in f-m sonar. Further investigation of the enhancement problem appears fully justified, in view of the potential value of a successful audible doppler enhancer.

4.20 DESCRIPTION OF ADE CIRCUITS

First ADE

Figure 49 shows the block diagram of a frequency doubler. The audio output of the QC

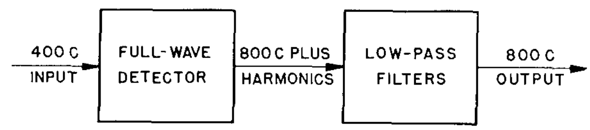


Figure 49. Block diagram of first ADE.

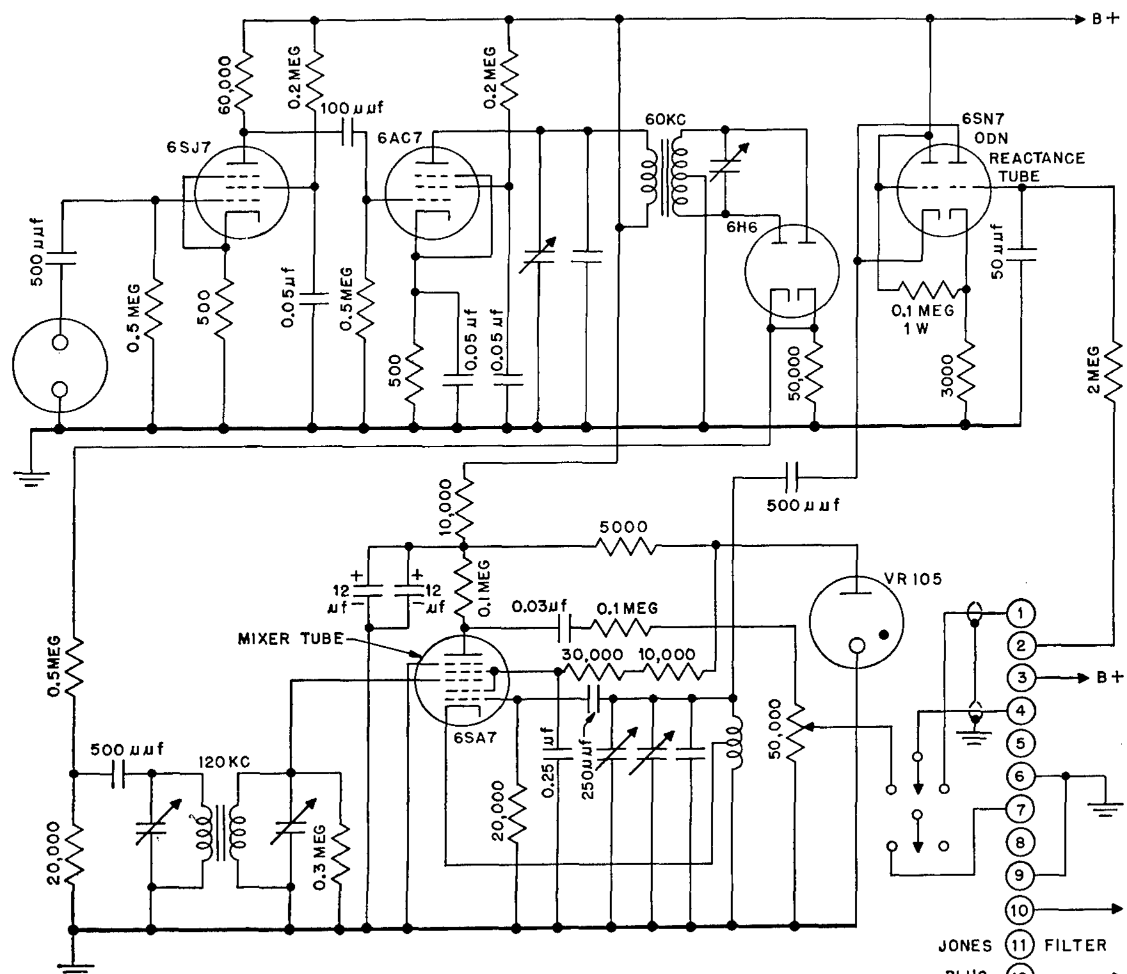


Figure 50. Schematic diagram of second ADE.

receiver is tuned to 400 cycles per second and then introduced into a full-wave detector. If the input is undistorted, the output will contain frequencies and harmonies of 800 cycles per second but no 400-cycle components. This method

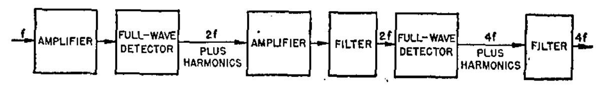


FIGURE 51. Block diagram of third ADE.

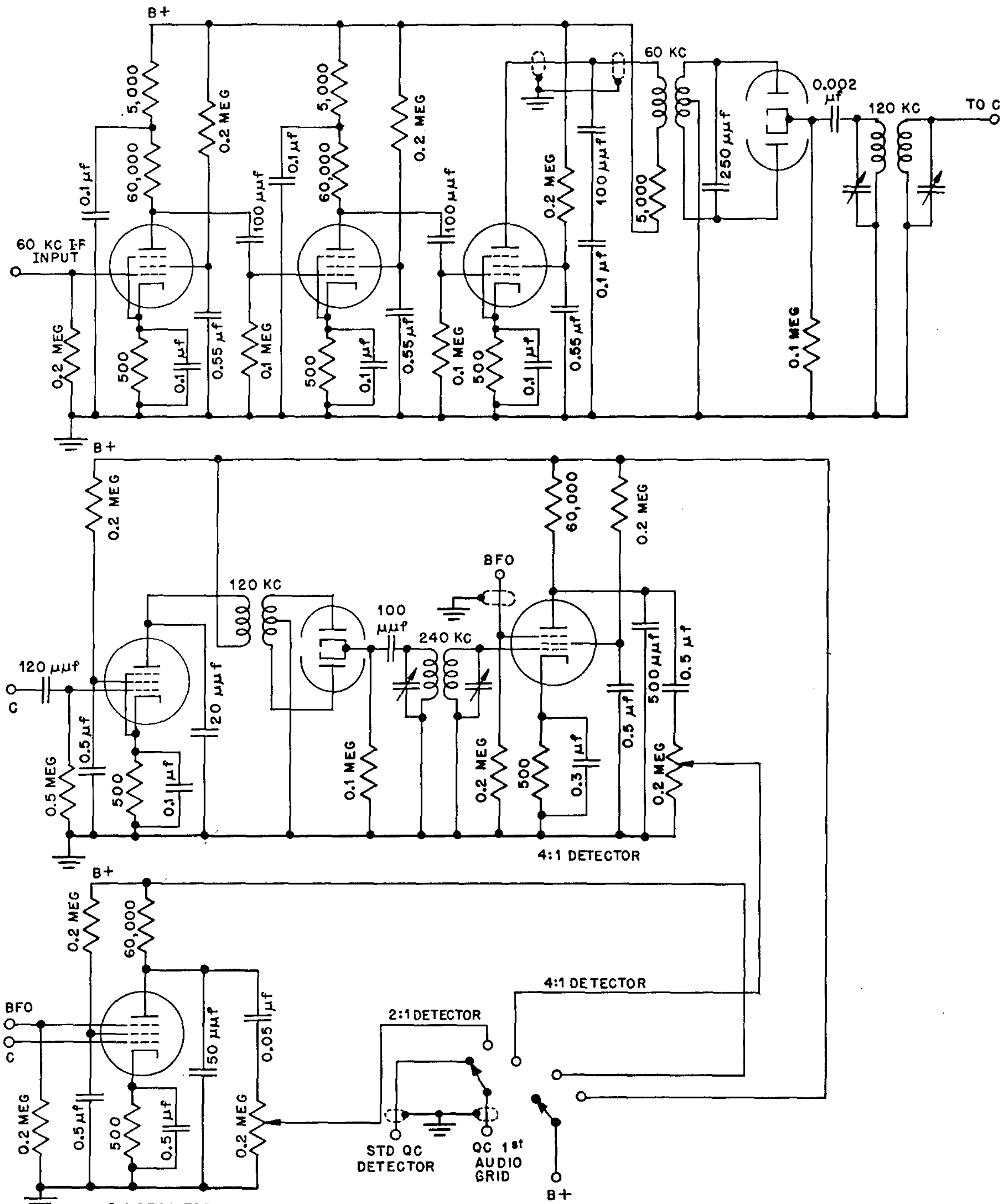


FIGURE 52. Schematic diagram of third ADE.

has the drawback that if the input is distorted unsymmetrically, the output will contain some 400-cycle components which are difficult to filter. These difficulties are avoided if the input signal is made 1,600 cycles per second although this change requires an additional mixer tube and oscillator circuit.

Second ADE

If a mixer tube is added and an intermediate frequency is used, there is no further complication and the problem of filtering becomes much easier. Figure 50 is the schematic diagram of an ADE using a circuit of this type operating on an intermediate frequency of 60 kc.

Third ADE

Figure 51 is the block diagram of a frequency quadrupler which is based on two sections of the frequency doubler shown in Figure 49. Figure 52 shows a detailed circuit by means of which a 1/1, a 2/1, or a 4/1 doppler enhancement may be selected.

This ADE circuit was sea tested but when the 4/1 enhancement ratio was used, any improvement in doppler recognition was largely nullified by the deterioration of tone quality. Moreover, large down-dopplers appeared to be lost rather than enhanced. With 2/1 enhancement, doppler recognition was improved for both up- and down-doppler, although tone quality still suffered.

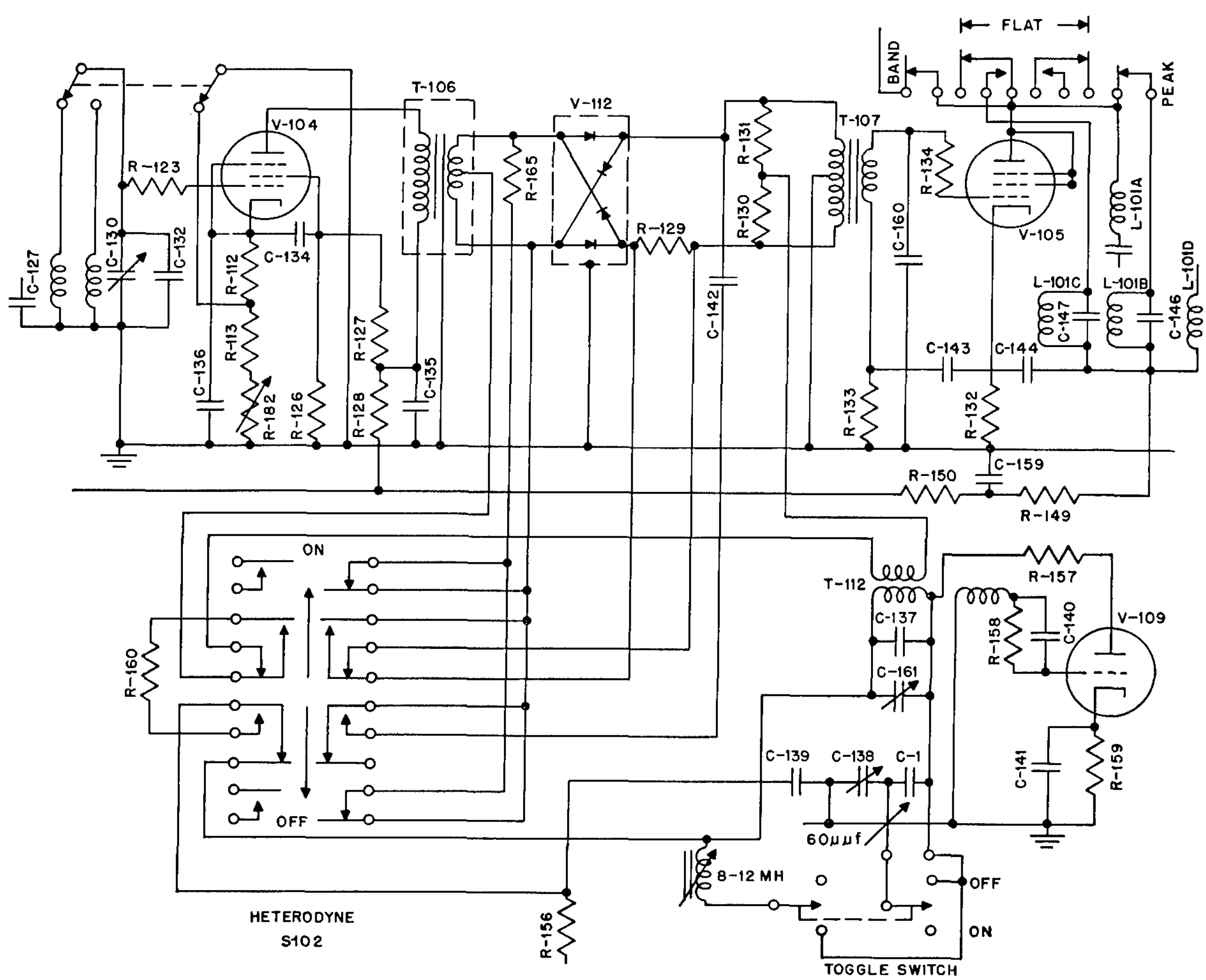


FIGURE 53. Schematic diagram of fourth ADE.

Fourth ADE (the Doppler-Doubler)

Among the large variety of arrangements by which beat-frequency products can be combined to produce doppler enhancement is that shown in Figure 53, an arrangement which was incorporated in the echo-ranging conversion unit.[4] In this scheme, a 60-kc intermediate frequency is heterodyned against a frequency of 120.8 kc yielding a signal at 60.8 kc. This in turn beats again with the original 60-kc signal to yield an audio signal of 800 cycles per second. Suppose that a signal with a down-doppler of 100 cycles per second is received. The i-f signal then becomes 60.1 kc and the first beat-frequency signal is 60.7 kc. Then the audio frequency is 600 cycles per second as compared to the normal 700 cycles per second (800 minus 100 cycles per second), so that frequency doubling has been achieved. Since the intensities of the 60-kc signal and the 60.8-kc signal, which are heterodyned to give the final audio note, are each proportional to the strength of the incoming signal, the amplitude of the audio signal is proportional to the square of the amplitude of the receiver input signal.

This operation as a square law device results in some additional gain on fairly strong doplerized echoes, and in an apparent narrowing of a projector beam which facilitates the obtaining of accurate bearings. However, the same square law feature gives rise to cross-modulation products which render the output highly discordant, thus partially nullifying the expected auditory advantages. Moreover, an even more serious drawback is found in an inherent tendency to favor the reverberation background at the expense of any echo signal of somewhat lesser intensity. These disadvantages finally prevented acceptance by the Navy.

Fifth ADE

Figure 54 is the block diagram of an ADE circuit that makes use of a discriminator such as is employed in the ODN circuit. The doppler enhancement operates on the following principle.

The frequency shift of the echo generates a voltage in the discriminator. This voltage is applied to a reactance tube, which controls the BFO in the listening amplifier circuit, with such a polarity that the frequency shift of the echo is greater than would be normally obtained.

In the experimental chassis, the signal is fed into a three-stage pentode limiter at 60 kc through a cathode follower connected to the grid of the final i-f amplifier in the 755 receiver. The 60-kc signal is heterodyned with a 60.8-kc 6J5 oscillator in a 6SA7 mixer tube. The plate circuit of the 6SA7 tube feeds a two-stage a-f amplifier consisting of a 6SQ7 triode and a 6V6 tube. The 6V6 tube drives a high-Q, two-coil discriminator of the type used in the Model II ODN. The output of the ODN discriminator is switched shortly after a ping and enhances doppler during the remainder of the interval between pings. Both the 60.8-kc oscillator in the ADE and the 60.8-kc oscillator in the 755 receiver are controlled by 6SJ1 reactance tubes. The oscillator LC ratios and the voltages to the reactance tubes are adjusted so that the two oscillators track when the same d-c voltage is applied to the reactance tubes. In operation, both beat-frequency oscillators are set to the same frequency with the grids of the reactance tubes grounded. Then, when the voltages on the reactance tubes go up and down together, as during the ODN interval, the two oscillators remain together in frequency.

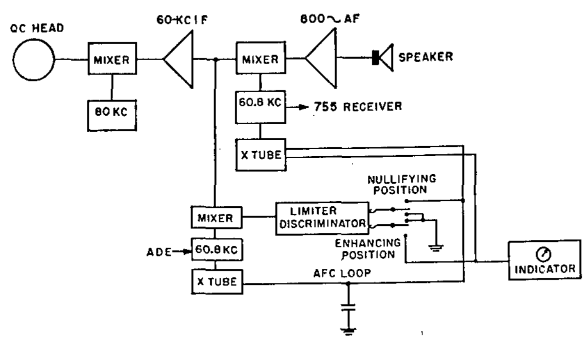


FIGURE 54. Block diagram of fifth ADE.

In laboratory tests, this circuit operated satisfactorily. It is not expected that the discriminator system will be troubled by cross-modulation products. However, since the enhancement is obtained by a limiter-discrimi-

nator combination, a voltage which is 3 db below reverberation level will receive no enhancement whatever. Furthermore, an echo must be 3 db above the level of reverberation to receive maximum enhancement.

The disadvantage of this particular setup is the tendency of the two oscillators to drift apart in frequency over a long period of time. Thus it can happen that, though the two oscillators do go up and down simultaneously and by equal amounts during nullification, the output of the 755 receiver drifts to a frequency other than 800 cycles per second. Since the frequency of the oscillator in the ADE is always brought to 800 cycles per second, because it is in the AFC loop, the output of the 755 receiver will always be the one which drifts. The remedy is to use a separate discriminator, operated from the output of the 755 receiver, to set that output to 800 cycles per second independently during nullification. After nullification, the system operates once more as the present one does, enhancement voltage being fed from the ADE discriminator to the reactance tube in the 755 receiver. This system is free of all tracking and drift problems. Furthermore, if it is found advantageous to operate the ADE discriminator at other than 800 cycles per second, this can be done without difficulty. In the interests of increased frequency range and linearity for indicator operation and in the interests of small size, for example, it might be desirable to operate the ADE discriminator at a higher frequency, such as 2 kc.

An additional advantage of this system lies in the fact that the degree of enhancement may be controlled merely by varying the amount of enhancement voltage fed from the discriminator in the ADE to the reactance tube in the 755 receiver.

4.21 CONCLUSIONS AND RECOMMENDATIONS

The desirability of enhancing the doppler shift of a returning echo in order to increase the certainty and ease with which the operator can interpret doppler information concerning target movement is sufficient to justify further work on enhancement methods. Although it has been shown to be possible to construct frequency doublers which provide either a linear or square law response to the intensity of the echo signal, study of these circuits has emphasized the need for independent inquiry concerning the desirability of square law or higher power response.

The investigation of electronic circuits utilizing nonlinear elements for the production of multiple-frequency terms seems to have been sufficiently extensive to demonstrate that such effects are always attended by other undesirable modulation products which cannot be removed by conventional filters. This problem is aggravated by the coexistence of noise signals comparable in strength to the desired echo. In all the circuits for frequency multiplication which were studied, the existence of undesired cross modulation between the desired signal and noise led to so serious a degradation of tone quality as to make the doppler enhancement undesirable from an operational point of view. Preliminary analysis indicated that this will always be the case, although the generality of the conclusion should be confirmed by further analysis.

Various schemes have been proposed for achieving frequency multiplication by other methods which would avoid the difficulties of tonal depreciation. The most frequent suggestion involves the use of a short, endless loop of magnetic recording wire whose signals would be picked up by a series of pickup units arranged to move relative to the wire in such a way as to enhance the doppler effect. A more feasible scheme involves borrowing television techniques whereby the incoming signal would be effectively scanned at such a rate as to multiply all frequencies involved without generation of spurious frequency components. A modification of this scheme has been under study by the San Diego laboratory in connection with f-m sonar[a] and should be investigated in connection with any further work with doppler enhancement which is undertaken.

[a] See Division 6, Volume 17.

Chapter 5

BEARING DEVIATION INDICATOR

Bearing Deviation Indicator

The bearing deviation indicator [BDI] is a device which indicates on a cathode-ray tube screen, for each echo received, whether the target is to the right or to the left of the bearing of the ship's sonar projector. In operation, each ping transmitted by the sonar equipment produces at the lower edge of the CRO screen a luminous spot which sweeps vertically upwards. If no echo is returned, the trace on the screen is a straight luminous line except for random deflections caused by reverberation. When, however, an echo is received, the moving spot is deflected to the right or left depending on whether the reflecting target is to the right or left, respectively, of the projector bearing. If the projector is trained on the target, the spot either brightens without deflecting or shows a slight double reflection. The distance the spot travels up the screen before deflecting or brightening is proportional to the range of the target. The developmental work on BDI was performed by the Harvard Underwater Sound Laboratory.

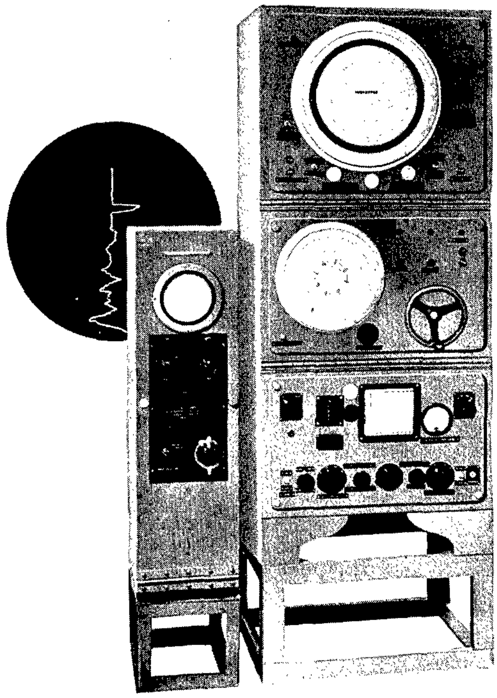


FIGURE 1. Bearing deviation indicator shown with echo-ranging stack.

5.1 INTRODUCTION

The bearing deviation indicator was developed to increase the accuracy of locating an underwater object by echo ranging. Before the advent of BDI most U. S. Navy echo-ranging gear belonged to the QC series. With this equipment, target bearing is determined by the cut-on method which consists essentially in locating the two ends of the target by echo ranging and then averaging these bearing values to determine the target's center bearing. This method requires at least five pings for every center bearing, since at least two are necessary to locate each end of the target (one on the target and one off) and one or more echoes are received while the operator is sweeping the sound beam between ends of the target. Experience has demonstrated this procedure to be necessary because the breadth of the sound beam is so great that a target bearing of sufficient accuracy cannot be obtained with one ping. The method is wasteful of time since under the very best conditions only two of every five pings give bearing values that can be used in the determination of the center bearing, which is itself inaccurate by the amount that the target moves between the determinations of the cut-ons.

The BDI equipment, which utilizes a split projector, provides the sound operator with a right-left sense with respect to a target, thereby enabling him to obtain more and better information. The operator can see, for every ping, whether the target is predominantly to the right or to the left of the projector's bearing. He can, therefore, correct the projector's bearing after each echo, and thus determine the target bearing with greater accuracy and rapidity than is possible with the standard echo-ranging equipment.

During the early stages of World War II, the British developed a similar system which utilized two projectors as contrasted with the HUSL split projector.

Final Design

After satisfactory performance and approval by the U. S. Navy, Model X-3 BDI and Model X-4 BDI were designated as production prototypes.[1] In the circuit of Model X-3 the two receiving channels are translated by heterodyning to occupy adjacent positions in the frequency spectrum. They are amplified in a single-channel amplifier, the gain of which can be varied at will without disturbing the amplitude balance between the two channels.

Considerable engineering development work remains to be done in simplification of the circuits required to yield BDI and in providing for more reliable operation and easier maintenance. Suggestions concerning fruitful lines of attack on these objectives are made in Section 5.10.2. It is also suggested that particular emphasis be devoted to developments leading to a more effective utilization of doppler effect for simplification of the deviation indications and for providing easier discrimination between a target and its wake.

5.2 BASIC PRINCIPLES OF BDI

5.2.1 General Theory

In the first part of this section, the general theory of *simultaneous lobe comparison* [SLC] is discussed. Following this, the specific circuits of various types are considered individually.

It is possible to feed the electrical outputs of an array of individual hydrophones, each of which may be considered as a small generator, through separate phase-shifting networks and then combine them to give a particular directivity pattern. Furthermore, a second set of phase-shifting networks can be connected to the hydrophone array at the same time, and a different directivity pattern obtained through the combination of the two sets. In fact, if proper impedance relations are observed, any required number of sets of phase-shifting networks can be connected to the hydrophone array and that number of separate directivity patterns can be realized simultaneously in separate channels. This may be considered the basic principle of simultaneous lobe reception.

The simplest possible array,[1] of course, consists of two hydrophones. An echo-ranging projector with separate connections brought out from the electrical elements in the left and right halves is an example. Splitting of this kind is shown schematically in Figure 2 for both magnetostrictive and piezoelectric transducers. For such a projector, when outputs A and B are combined directly, the directivity pattern is that of the complete circular face. However, when output A is lagged in phase with respect to B by an angle θ, the directivity pattern is

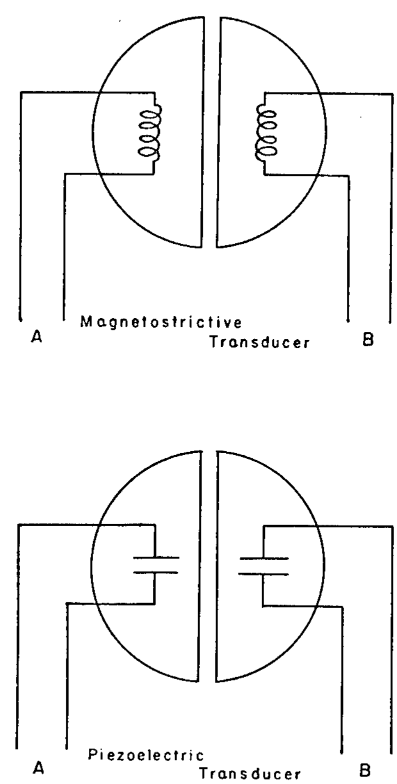


Figure 2. Schematics of projectors split for BDI.

changed. It then corresponds approximately to the pattern that would be obtained if microphone A were set back from B by a distance such that the phase lag in the water would be θ degrees, and the outputs were then combined

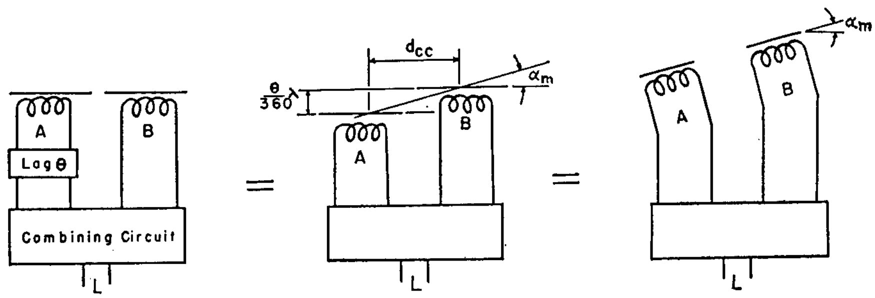


FIGURE 3. Effect of lagging one half of projector.

directly. Or in other words, as is shown in Figure 3, the effect of lagging the output of one-half of the projector by a phase angle θ is approximately the same as that of turning the projector. More specifically, it is equivalent to rotating the whole projector through the angle α_m, given by

$$\alpha_m = \sin^{-1}\frac{\lambda\dfrac{\theta}{360}}{d_{cc}},$$

where d_{cc} = distance between effective centers of the two projector halves, and

λ = wavelength of sound in water.

A shifting of the pattern in the other direction can be achieved by inserting a phase lag in B with respect to A before combining the two outputs.

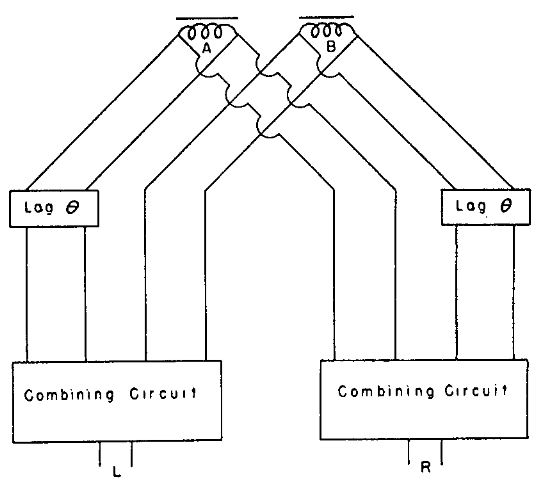


FIGURE 4. Method of obtaining left- and right-steered lobes simultaneously.

Now if one network is used to produce lag in B with respect to A, and simultaneously a second network is used to produce lag in A with respect to B, the outputs of the two networks produce two divergent patterns. The method

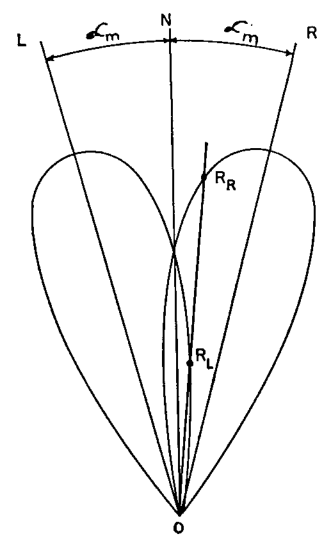


FIGURE 5. Simultaneous shifted lobe patterns.

of accomplishing this is shown in Figure 4 where channel L has a left-steered lobe and channel R a right-steered lobe. A sample of the simultaneous shifted lobe patterns is given in Figure 5. The angle α_m through which the main lobe is shifted is a function of the angle of lag θ and of the width and shape of the projector. For a circular face of diameter d, it is given by

$$\alpha_m = 0.26\frac{\lambda\theta}{d}.$$

Figure 6 shows a series of directivity patterns (R) calculated for a split circular projector with a diameter of four wavelengths ($d = 4\lambda$) with different values of the lag line θ.

In order to use the shifted patterns to give an

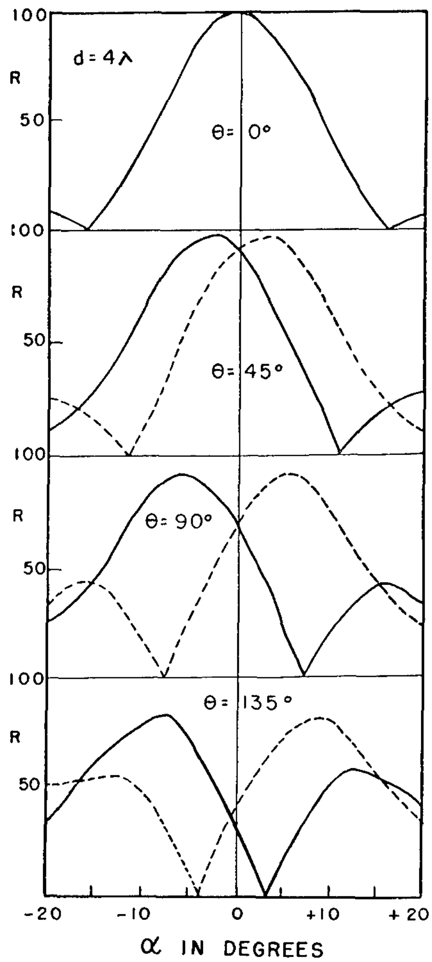


FIGURE 6. Calculated shifted patterns.

indication of deviation from the normal ("on" in Figure 5) the amplitudes R_R and R_L, in the right-steered and left-steered channels, may be compared in various ways. As explained below, the amplitudes which are compared in BDI operation are not those from the projector halves, but are the amplitudes in right- and left-shifted channels. Initially the signals from the halves of the split projector are equal in amplitude, but differ in phase. The BDI lag line transforms this phase difference into an amplitude difference which has deviation sense. The difference between the amplitudes in the right and left channels is indicated to the operator and he continually adjusts the bearing of the projector to keep this difference indication as small as possible. Figure 7A shows curves of the difference $R_R - R_L$ for the patterns given in Figure 6 for listening to a distant source of constant amplitude. It will be noted that the difference increases with increasing deviation up to the angle of the first zero; up to this point, the difference indication is unambiguous both as to sense and

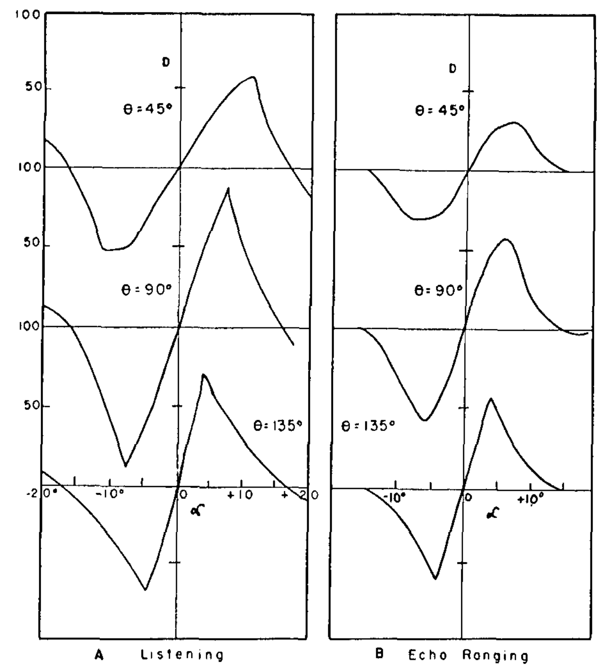


FIGURE 7. Difference curves for patterns of Figure 6.

magnitude of deviation angle. Beyond this point, as the difference decreases to zero (when $R_R = R_L$), the difference indication is unambiguous only with respect to sense.[1]

In echo ranging, the amplitude of the received echo depends upon both the transmitting and receiving patterns. The shifted receiving patterns must therefore be multiplied by the transmitting directivity pattern before differences are taken. Figure 7B shows the difference curves under echo-ranging conditions. In the unambiguous region, they differ very little from the listening curves.

Some general properties of the difference curves are worth noting. The region over which the curves give unambiguous sense of deviation is the same for all values of the phase shift θ and, for reasonably narrow patterns, is given by

$$2\alpha = 2.70\frac{\lambda}{d},$$

where λ and d are as defined above. The region which is unambiguous in both sense and magnitude of deviation, however, becomes narrower as the phase shift θ increases, being

$$2\alpha = 2 \times 0.37\frac{\lambda}{d}(180^\circ\ \theta).$$

At the same time the sensitivity S (rate of change of difference with deviation) becomes greater. Values of these quantities can be read from Figure 8. Choice of the value of θ, therefore, depends on three conflicting factors:[1a]

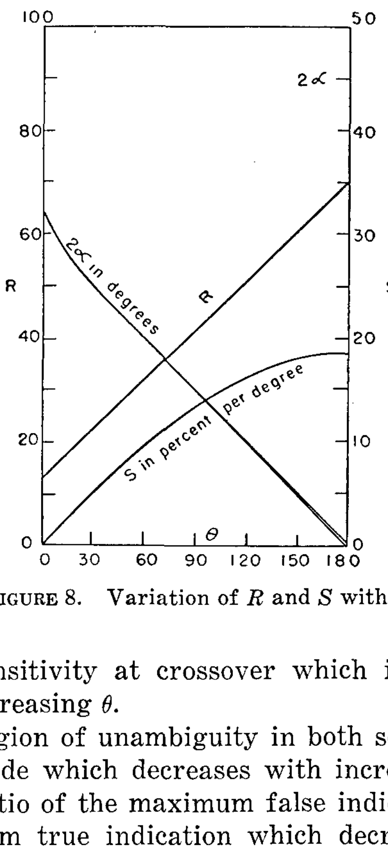


FIGURE 8. Variation of R and S with θ.

1. Sensitivity at crossover which increases with increasing θ.
2. Region of unambiguity in both sense and magnitude which decreases with increasing θ.
3. Ratio of the maximum false indication to maximum true indication which decreases as θ increases.

In most of the early work done on BDI, a value θ equal to 60 degrees was used and found to be satisfactory, although later experience indicated that improved performance might be obtained with somewhat larger angles. In more recent work, θ has usually been taken between 75 and 90 degrees. No very adequate sea tests have been made with regard to this point, and it is possible that a still larger θ would give adequate performance. The exact value used, however, does not seem to be critical.

Up to this point it has been assumed that the sensitivities of the two halves of a receiver are equal. This is not necessarily the case; indeed, it is quite unlikely. An investigation of the effects of amplitude unbalance showed that the zero indication is not affected, but that the sensitivity decreases slightly for moderate amounts of unbalance.[2] For example, if one projector half is twice as sensitive as the other, the deviation sensitivity is reduced by only 20 per cent. It may, therefore, be concluded that sensitivity differences are relatively unimportant, particularly in nonproportional BDI systems, where the sense of the deviation rather than its exact magnitude is of interest.

With an actual transducer, it is to be expected that there may also be a relative difference in phase between the electrical outputs of the two halves, even when the sound source is exactly on a line normal to the face. Such a differential phase shift may be introduced by differences in the electromechanical systems or in the electrical circuits, and may vary with frequency. Its effect is to produce an equivalent shift in the center bearing, that is, the bearing at which $R_R = R_L$. At 21 kc, for instance, an electrical phase difference of 15 degrees between the two projector halves gives a bearing error of 1 degree. Therefore, it is important that such phase differences be kept small.

In the BDI the lag circuit is connected across the output of the two halves of the projector. Current from one projector half which crosses over to join that from the other half thus suffers a phase lag. That current which goes directly on, without going through the lag line, is not given this phase shift. In this way the projector is made to "look" to the right and to the left simultaneously. In addition, an output is taken from the center of the lag line, in which case the projector looks straight ahead, since the lag line retards both signals going through it by an equal amount. The output of the center of the lag line, which is the same as the output of the unmodified projector, goes to the standard sonar gear, which thus functions in the normal manner. The BDI uses the outputs of the two ends

of the lag line, employing the left and right sensitivity of these channels to get the left or right indication of target position.

Reduced to its simplest form, the BDI may be considered to consist of a split projector, a lag line, and an indicating meter, as shown in Figure 9.

If an echo approaches from a bearing about 4 degrees to the left of the projector bearing, the left half of the projector is a little nearer to the target than the right half, so that the current in the left half leads by part of a cycle. By the time these currents are combined in the left channel, however, the lag line has delayed the current from the left half, so that it is in phase (or very nearly so) with the current from the right half. These currents would add, therefore, to give the left channel a relatively large current. The effect of the lag line on the right channel, however, is essentially the reverse of the above. The current from the right half of the projector, which already lags that from the left half, is further delayed by the lag line. This puts the two currents even more out of phase so that when combined they partially cancel, making the net current in the right channel relatively small. Now a meter, a CRO tube, or other indicating device to which the difference in amplitude of the two channels is applied, will indicate that the target is to the left of the projector bearing since the left channel carries the stronger signal.

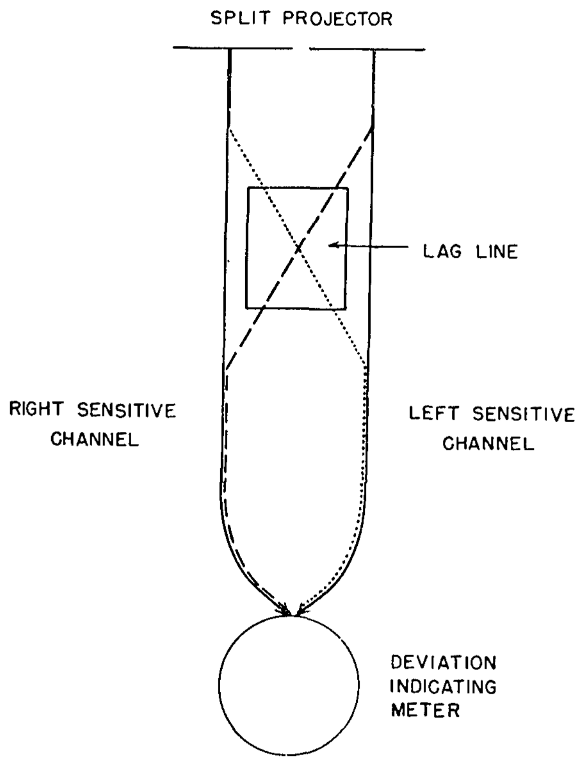


FIGURE 9. BDI reduced to simplest form.

If the echo comes from the right, the right-channel current is the larger and a right target indication will result. For an echo coming from the exact projector bearing, the currents in the two channels are equal and neither a right nor a left target indication will be given.

Thus, what begins as a difference in phase between the currents from the two projector halves becomes, through the action of the BDI circuits, a difference in amplitude which is employed to give the deflection on the BDI screen.

5.2.2 Comparison of BDI Systems[3]

The principles of the operation of the following five BDI systems are here compared:

1. HUSL Model X-3. A simultaneous lobe comparison system formerly called SLC.
2. HUSL Model X-4. A modulation system.
3. Radio Corporation of America *vector bearing indicator* [VBI]. A sum-and-difference system; also called *right-left indicator* [RLI].
4. HUSL Undesignated System. A sum-and-difference system similar in behavior to the vector bearing indicator.
5. Bell Telephone Laboratories *phase actuated locator* [PAL]. This system has been used only for noise listening.

HUSL MODEL X-3

The essential parts of the HUSL Model X-3 BDI are shown in Figure 10. During operation, two signals of equal amplitude V and phase difference $2a$ are produced by the two projectors. The two voltages may be written as

$$\begin{aligned} V_1 &= V \cos(\omega t + a) \\ V_2 &= V \cos(\omega t - a). \end{aligned} \tag{1}$$

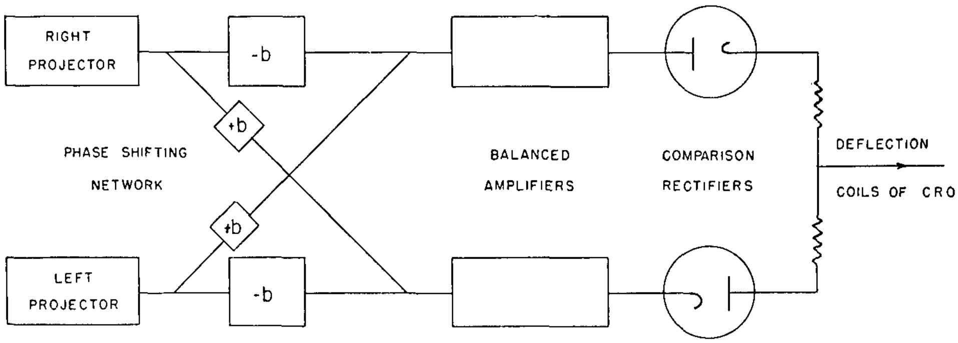


FIGURE 10. BDI system using phase-shifting network—HUSL Models X-3 and X-4.

These two voltages are combined through a phase-shifting network [a] to form two new voltages (V_3 and V_4), which are in phase but differ in amplitude. One of these (V_3) is the mean of V_1 and V_2 after V_1 is advanced through an angle b and V_2 is retarded by the same angle. The other (V_4) is a similar mean except that V_2 has been advanced and V_1 retarded. These voltages may be written:

$$\begin{aligned} V_3 &= \frac{V}{2}[\cos(\omega t + a + b) + \cos(\omega t - a - b)] \\ V_4 &= \frac{V}{2}[\cos(\omega t + a - b) + \cos(\omega t - a + b)], \end{aligned} \tag{2}$$

which are equivalent to

$$\begin{aligned} V_3 &= V \cos \omega t \cos (a + b) \\ V_4 &= V \cos \omega t \cos (a - b). \end{aligned} \tag{3}$$

The voltages in equation (3) are the two shifted lobes referred to above. They are amplified and passed into a comparison rectifier which produces the difference of their amplitudes.

$$|V_4| - |V_3| \sim |V| [|\cos(a - b)| - |\cos(a + b)|] \tag{4}$$

The voltage output V of one projector is just the pattern of the projector expressed in the variable a. For the particular case of two adjacent rectangular projectors of total width L,

$$V = \frac{(\sin a)}{a}, \tag{5}$$

and

$$a = \left(\frac{1}{4}\right) kL \sin y, \tag{6}$$

where k is the wave number of the incident sound and y is the angle it makes with the normal to the line joining the projector.

As has been pointed out, the BDI measures a combination of phase and amplitude. In the HUSL systems, this is done by first converting the phase difference into an amplitude difference by means of the phase-shifting network described above. To the right of the phase-shifting network in Figure 10 only amplitude is measured and phase is of no consequence. It is for this reason that the gain through the two amplifiers must be closely balanced. Such balance, however, is extremely difficult to accomplish in amplifiers which have grid control of gain. Since amplifiers of this type are desirable in echo ranging, the two modifications of Figure 10 which are embodied in the X-3 and X-4 models have been developed at HUSL.

In Model X-3 (see Figure 11) the frequencies at the output of the phase-shifting network are converted to two different intermediate frequencies which are passed through a common amplifier. At the output of this amplifier, separation of the two channels is accomplished by means of filters. The operation of this circuit is the same as for Figure 10 and the voltages given by equations (1) through (6) apply to both cases.

[a] The phase-shifting network as shown consists of a pair of lead sections ($+b$) and a pair of lag sections ($-b$). Less complicated networks such as a single lag or lead section connected between channels can be used. The advantage of the arrangement shown is that the differential phase shift can be held approximately constant and the differential attenuation small over a range of frequencies. The same remark applies to the 45-degree lag and 45-degree lead section in VBI [RLI] and PAL instead of the conventional single 90-degree section.

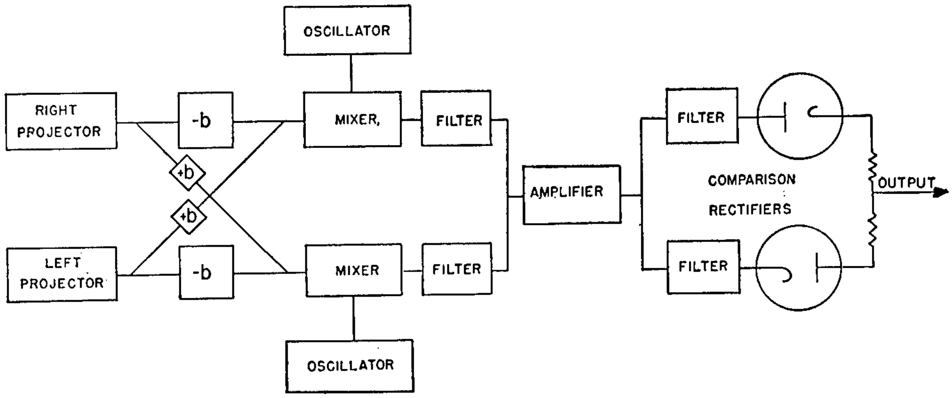


FIGURE 11. Model X-3 block diagram

HUSL MODEL X-4

The second modification, Model X-4, also uses a single-channel amplifier as shown in Figure 12. The electronic switches connect alternately the two outputs of the phase-shifting network to the common amplifier. The switching frequency provided by a local oscillator is about one-fiftieth of the signal frequency so that some 25 cycles of signal frequency in each channel are viewed alternately by the system. The output of the amplifier is demodulated and the fundamental of the switching frequency f_m is selected by a filter. Finally, the phase-sensitive rectifier gives a d-c output which is proportional to the difference in amplitude in the left and right channels. Equations (1) to (6) are applicable, and the output voltage is given by equation (4).

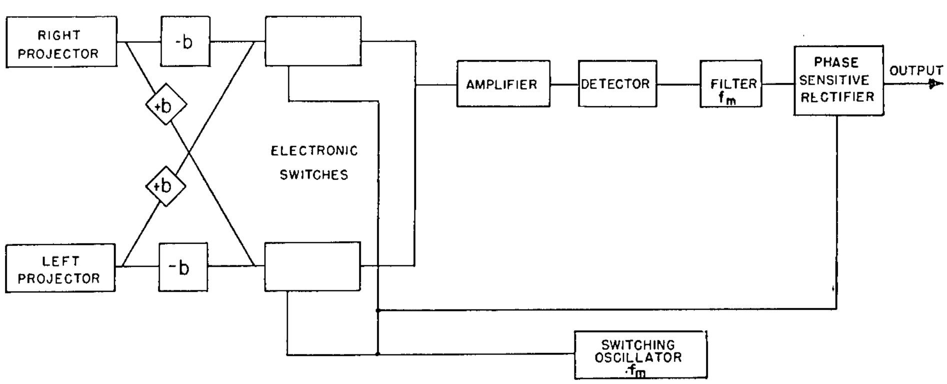


FIGURE 12. Model X-4 block diagram.

In Figure 13 are shown three BDI deflection curves expected with the three following systems using a single 60-degree lag line:

a. Double i-f system with linear detection.

b. Modulation system with linear detection.

c. Modulation system with square law detection. In the last two cases 100 per cent modulation is assumed.

It will be noted that the curves a and b are identical up to the point

$$\theta = \pi - B = 120°,$$

where $B = 2b$ is the phase shift introduced by the lag line. Beyond this point, they begin to differ slightly. Experimentally it has been found that this difference is too small to be detected. On the other hand, system c shows a marked departure from a and b. The form of c is independent of B.[4] The first portion of a and b is more nearly linear than the corresponding part of c. This may be an important advantage in some applications.

Although systems a and b are equivalent in echo ranging where a single frequency is used, it has been found in practice that they give

different results when trained on noise. System a gives good indication on noise, whereas system b gives large random indications if the percentage modulation is low. When the percentage modulation is made appreciably greater than 100 per cent, this difference disappears. The difficulty with b at low modulation has been attributed to a spread in frequency of the noise, which represents modulation at the same frequency as the switching frequency. In Model X-4, the modulators are designed to give a strongly overmodulated output in order to overcome the difficulty. One may consider the input signals to be switched on and off rather than modulated in the usual sense.

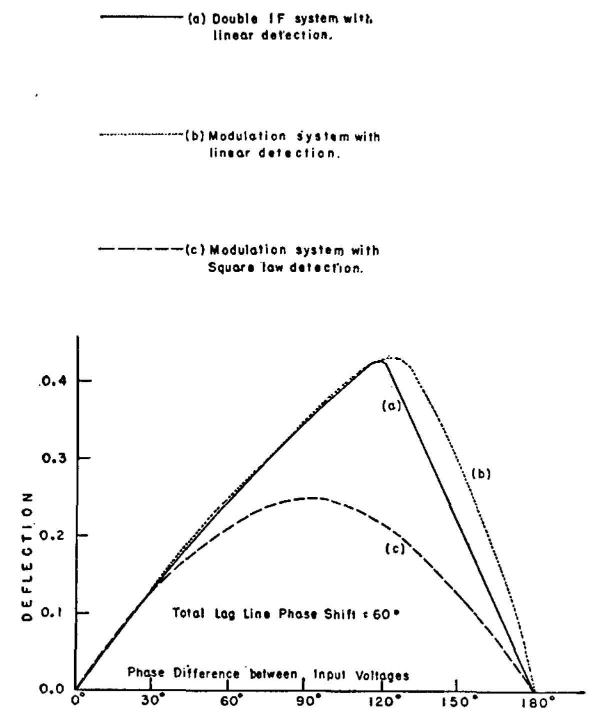


FIGURE 13. Deflection vs input phase difference.

VECTOR BEARING INDICATOR OF RCA.[5]

The VBI may be called a sum-and-difference system. The essential circuit used in it is shown in Figure 14. In this case the two voltages [see equation (1)] are combined at the input to form the sum and difference V_s and V_d, respectively, where

$$V_s = 2V \cos \omega t \cos a,$$

and

$$V_d = 2V \sin \omega t \sin a. \tag{7}$$

These voltages, which are 90 degrees out of phase, are then amplified through two amplifiers having gains G_s and G_d. The phase difference is compensated for by a relative phase rotation of 90 degrees in the two channels and the two outputs are recombined in the phase-sensitive detector. The voltages across the diodes are:

$$G_sV_s \angle 45° \pm G_dV_d \angle -45° = V\sqrt{G_s^2 + G_d^2} \cos\left(\omega t \frac{\pi}{4}\right) \cos (a \pm b), \tag{8}$$

where

$$\tan b = \frac{G_d}{G_s}. \tag{9}$$

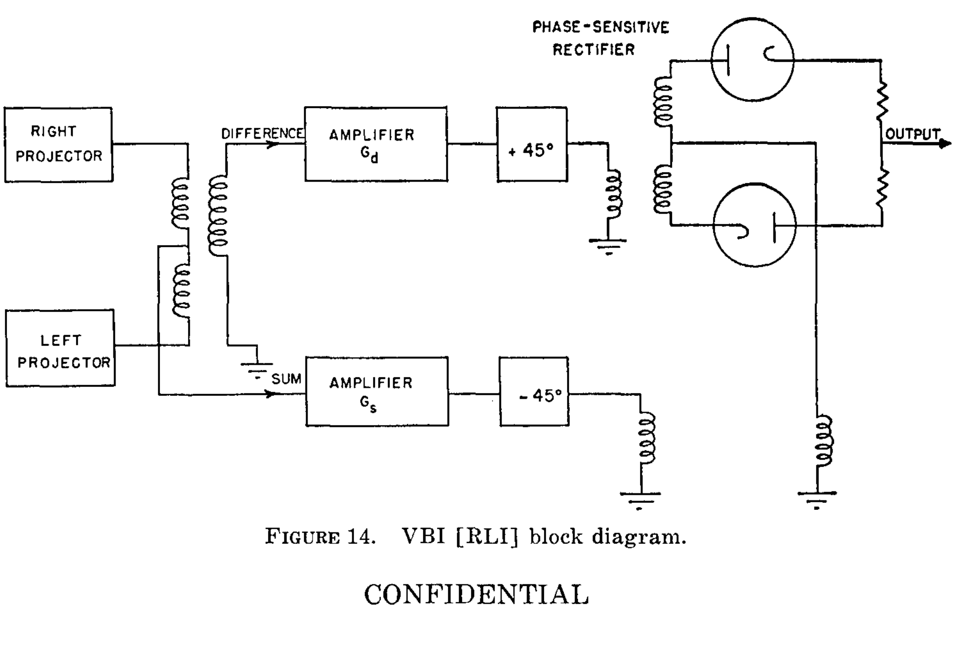


FIGURE 14. VBI [RLI] block diagram.

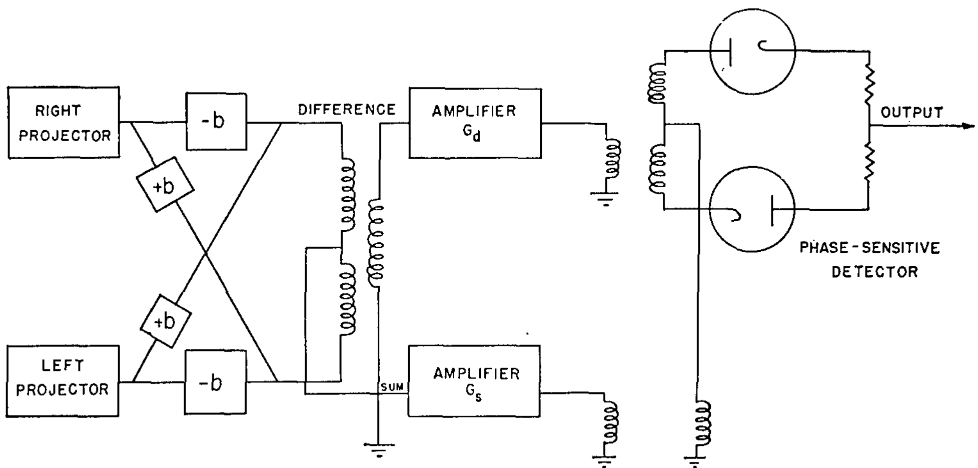


FIGURE 15. HUSL undesignated system block diagram.

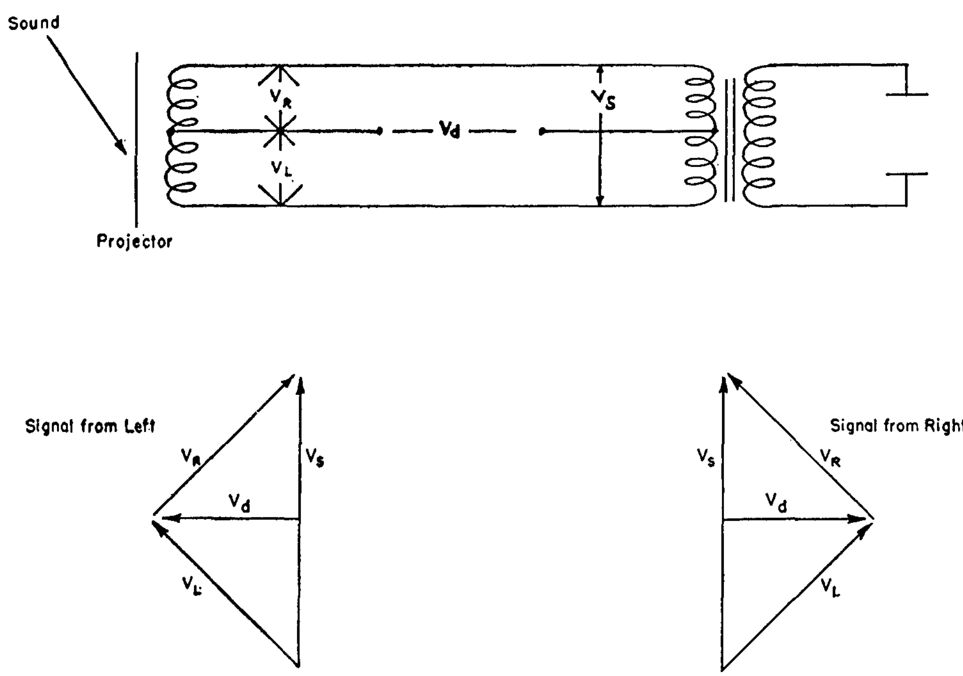


FIGURE 16. Basic principle of sum-and-difference BDI.

It is apparent that equation (8) is the same in form as equation (3) and therefore represents the same shifted lobes found in X-3 and X-4. The equivalent phase shift $2b$ of the phase-shifting network depends on the relative gains in the sum-and-difference channels according to equation (9).

HUSL Undesignated System

This system is also of the sum-and-difference type and behaves similarly to the VBI discussed above. The circuit, shown in Figure 15, employs a phase-shifting network of the type used in Models X-3 and X-4.

In the sum-and-difference method a voltage vector V_d is derived at right angles to the main voltage V_s across the whole projector. The magnitude and polarity of V_d depend on the direction of arrival and on the amplitude of the incident sound. After the voltages V_s and V_d are amplified in separate channels, one is shifted in phase by 90 degrees and the two are then combined in a phase-sensitive rectifier to give a d-c output whose sign depends upon the direction of arrival of the incident sound. This d-c output is used to give right-left indications.

In Figure 16 the direction-sensitive (difference) voltage V_d is taken between the center tap of the projector and the center tap of the input transformer. If the projector halves are wired series-opposing, V_s and V_d are interchanged, but the following analysis still holds.

If a plane acoustic wave falls upon the face of a square transducer obliquely, then the phase of the induced voltage in the two halves will be shifted with respect to that produced by a normally incident wave. Therefore,

$$V_L = V \cos(\omega t - b)$$
and
$$V_R = V \cos(\omega t + b). \tag{10}$$

In Figure 16 the difference of the voltages appears at V_d and their sum appears at the transformer output. Therefore,

$$V_d = 2V \sin \omega t \sin b$$
and
$$V_s = 2V \cos \omega t \cos b. \tag{11}$$

In the next stage of the system V_d and V_s are amplified in separate channels with different gains (G_d and G_s) and V_s is shifted in phase by 90 degrees. Hence the output voltages of the two channels are respectively (Figure 17):

$$V_d' = 2G_d V \sin b \sin \omega t$$
and
$$V_s' = 2G_s V \cos b \sin \omega t \tag{12}$$

These two voltages are applied to the phase-sensitive detector so that V_d' and V_s' are series-aiding on the upper rectifier and series-opposing on the lower. The voltages appearing across these rectifiers are (see Figure 17):

$$\text{Upper: } V \sin \omega t\ (2G_s \cos b + G_d \sin b);$$
$$\text{Lower: } V \sin \omega t\ (2G_s \cos b - G_d \sin b). \tag{13}$$

Rewriting these:

Upper:
$$2V\left[G_s^2 + \left(\frac{1}{2G_d}\right)^2\right]^{\frac{1}{2}} \cos(b - a) \sin \omega t;$$

Lower:
$$2V\left[G_s^2 + \left(\frac{1}{2G_d}\right)^2\right]^{\frac{1}{2}} \cos(b + a) \sin \omega t, \tag{14}$$

where
$$\tan a = \frac{G_d}{2G_s}.$$

Now compare these with the voltages at the output of the lag line in ordinary BDI. These voltages may be obtained from the input voltages [equation (10)], by adding the outputs of the two halves with phase shifts $(+a,-a)$ and $(-a,+a)$. They are:

Upper end of lag line:
$$V[\cos(\omega t - b + a) + \cos(\omega t + b - a)] = 2V \cos(b - a) \cos \omega t;$$

Lower end of lag line:
$$V[\cos(\omega t - b - a) + \cos(\omega t + b + a)] = 2V \cos(b + a) \cos \omega t.$$

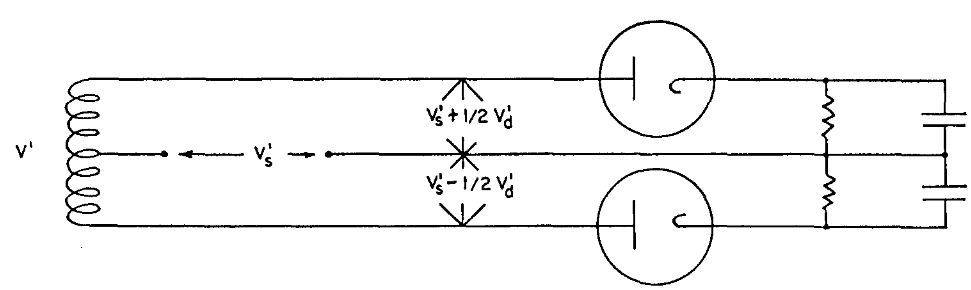


FIGURE 17. Voltages in sum-and-difference BDI circuit.

These voltages are identical in relative amplitudes with the voltages in equation (14). Thus, the sum-and-difference BDI is true SLC, since shifted lobes appear in the output of the lag line.

It will be noticed that the angle of phase shift a depends on the ratio of the amplitude of the difference-channel voltage to the sum-channel voltage. Therefore, the effective phase shift of the system may be easily varied by varying the gains of the two channels.

This system of BDI always gives a true center bearing. Although the relative phase of the sum-and-difference channels must be preserved for good BDI operation, any relative phase shift introduced will not affect the position of the center bearing indication.[3]

Phase-Actuated Locator [PAL] of BTL[5-7]

In the PAL system, shown schematically in Figure 18, the principal amplification takes place in the two separate projector channels, before any combining occurs.

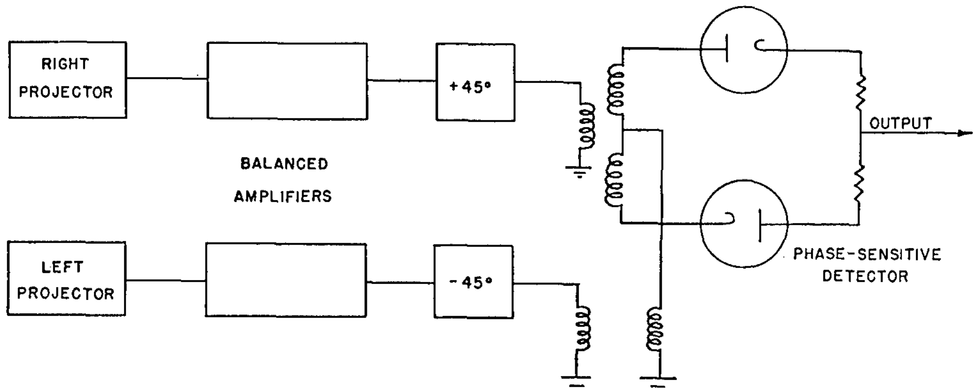


FIGURE 18. PAL block diagram.

Again, the input signals are given by equation (1). After balanced amplification and phase rotation of one channel by 90 degrees with respect to the other, there are two voltages proportional, respectively, to

$$V \cos(\omega t + a),$$

and

$$V \sin(\omega t - a). \tag{15}$$

The sum of these voltages is applied to one detector and the difference to the other. These may be written

$$2V \cos\left(\omega t - \frac{\pi}{4}\right) \cos\left(a + \frac{\pi}{4}\right),$$

and

$$-2V \sin\left(\omega t - \frac{\pi}{4}\right) \cos\left(a - \frac{\pi}{4}\right). \tag{16}$$

The output of the detectors is the difference of the amplitudes of the voltages given in equation (16). It will be noticed that the terms (16), except for phase and constant factors, are just the shifted lobes of equation (3) with the specialization $2b = 90$ degrees. Thus, the output of the PAL is the same as a Model X-4 which has a 90-degree phase-shifting network.

Description Summary

As indicated above, the output voltage is the same for each of the five systems considered, except that $2b = 90$ degrees in PAL. Thus, any comparison of the systems must be based on such factors as the extent to which departures from the theoretical performance are likely to occur in practice, difficulties of construction, and adjustment.

In spite of their apparent great differences, the five systems have a general procedure in common, which may be put under two headings.

Operation A. Two input signals differing in phase are converted into two signals differing in amplitude.

Operation B. The amplitudes of these two signals are subtracted to give the output indication. This subtraction may take place between

rectified d-c voltages, so that the sense of the difference is contained in the sign of the difference voltage, or it may occur between a-c voltages, in which case sense is lost and must be regained by examining the phase of the voltage relative to some comparison signal.

Before, after, and intermediate to these operations such necessary functions as amplifying, tuning, frequency changing, and filtering are introduced into the system. The principal difference between the systems concerns the point at which operations (A) and (B) occur. Table 1 gives a rough comparison of the systems from this standpoint. Ahead of the circuits that perform operation (A), unbalance in phase produces an error in bearing indication, but unbalance in amplitude is relatively unimportant. Similarly, between (A) and (B) unbalance in amplitude produces error while unbalance in phase is relatively less important. In the table, certain important parts of the systems have been omitted: e.g., in X-4, the principal amplifier which comes between steps 4 and 5, and in VBI, the principal amplifiers between steps 2, 4, and 5. These amplifiers do not introduce error by small amplitude or phase unbalance unless other sources of unbalance are simultaneously present (see Table 1). Also such obvious sources of deviation error as unbalance of the detectors themselves have not been included in the table.

Of the five systems considered, PAL seems the least promising from the standpoint of echo ranging. This is because all the amplification takes place in two physically separate channels and the introduction of tuning and *time varied gain* [TVG] or *reverberation controlled gain* [RCG] would make these virtually impossible to balance.

The principal disadvantages of the VBI and HUSL undesignated systems are (1) the variability in b due to relative changes in G_s and G_d when TVG or RCG is introduced, and (2) error resulting from unbalance in hydrophone sensitivity and unbalance in phase in the sum-and-difference amplifiers. No actual error is introduced by (1) but when b is in the vicinity of 45 degrees the deviation indication is optimum from the standpoint of false crossovers, linearity with respect to bearing deviation, and sensitivity. Thus, G_s and G_d should be closely the same and the farther their ratio departs from unity the more rapidly will the deviation indication deteriorate. The error (2) which was discussed earlier is expected to be much more serious than the corresponding error in X-3 and X-4 models. This is because the phase-shifting networks of X-3 and X-4 can be built to maintain the attenuation balance as closely as desired, without critical adjustment. On the other hand, the phase unbalance in the sum-and-difference amplifiers in VBI can be kept small only by careful alignment of the two channels.

The principal disadvantage of the X-3 circuit is its complexity which results in problems of adjustment, in particular the tracking of the

TABLE 1. Comparison of types of BDI.

	HUSL X-3	HUSL X-4	RCA VBI	HUSL undesignated	BTL PAL
1. Part of system sensitive to unbalance in phase	Input circuits preamplifiers	Input circuits preamplifiers	Input circuits	Input circuits preamplifiers	Input circuits principal amplifier 45° sections
2. Conversion of phase difference to amplitude difference (Operation A)	Phase-shifting network	Phase-shifting network	Vector addition and subtraction (simultaneous with 4 below)	Phase-shifting network (simultaneous with 4 below)	Phase-sensitive detector (simultaneous with 4 below)
3. Part of system sensitive to unbalance in amplitude	Principal amplifier	None	None	None	None
4. Comparison of two amplitudes (Operation B)	Comparison rectifier	Low-frequency switching (about 500 c)	Simultaneous with 2 above	Simultaneous with 2 above	Simultaneous with 2 above
5. Introduction of sense of comparison voltage 4	Not necessary	Phase-sensitive detector	90° differential phase shift—phase-sensitive detector	Phase-sensitive detector	Not necessary

two local oscillators and the alignment of the i-f filters. However, X-3 appears no more critical than VBI.

The greatest advantage of X-4 is its comparative simplicity and ease of adjustment. Since it uses one i-f channel with a single (modulated) frequency, it is less subject to unbalance than either X-3 or VBI. Its one disadvantage is its less satisfactory response to a localized source of noise containing frequency differences equal to the switching frequency.[8,9] It is believed, however, that this disadvantage is minor in echo ranging.

Neither X-3 nor X-4 is adapted to noise-listening over a wide frequency band. This is because the single i-f channel, which is necessary only when TVG is used in echo ranging, gives trouble with wide frequency bands.

The VBI system is satisfactory on broadband noise. In both VBI and PAL it is very desirable to split the 90-degree relative shift as shown in Figures 14 and 15 and use a lead element in one channel and a lag element in the other since then the 90-degree relative shift can be maintained over a wide band of frequencies without large amplitude unbalance. The VBI system is not well adapted to the use of *automatic volume control* [AVC], however, because of the different levels in the two channels and the desirability of holding the gains the same. Manual control of gain with balanced attenuators is therefore advised.

5.3 PHASE-SHIFTING CIRCUITS

CONSTANT-PHASE-SHIFT NETWORK[10]

The phase shift required in combining the output of the two halves of the projector into either BDI channel is independent of the frequency and size of the projector. This stems from the fact that the required deviation of the two beams is a fairly definite fraction of their own width.

In the X-3 models, the phase shift was accomplished by a single π-section lag line, and the phase shift was changed with frequency. Thus construction of a line of constant phase shift is a complicated task.

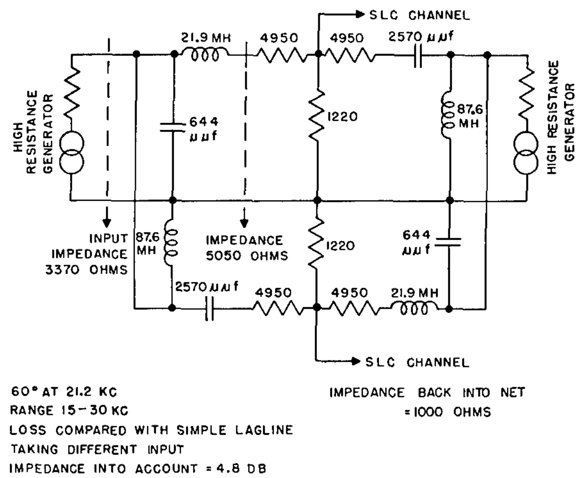


FIGURE 19. SLC network for wide frequency range.

Another possible approach is to use a lag line for one projector half, and a lead line for the other (see Figure 19). The phase constant of a lag line increases, and of a lead line decreases, with increasing frequency. Consequently there is a possibility of having one change nearly compensate the other over a range of frequencies.

There are a number of obvious advantages in the proposed network. It can be used at any frequency within its range and allows the same network to be installed with equipment to work at any frequency. It can also be used in echo ranging with a crystal projector where the operator might be able to select his frequency of transmission. Further it can be used in the reception of noise in a wide band and so make BDI the wide-band analogue of binaural listening. There are some advantages in regard to pattern in using a wide band, rather than a narrow one, in the reception of noise.

The proposed network has some disadvantages; it is more complicated, requiring four chokes instead of one, four condensers instead of two, and six extra resistors. Also it has no center tap for the listening receiver, which must therefore be bridged across the two channels somewhere else in the circuit.

Figure 20 shows a simpler circuit.[11] L and C are resonant at the center frequency. The phase shift with this circuit appears to change less with frequency than the previous circuit—less than half as much according to theoretical

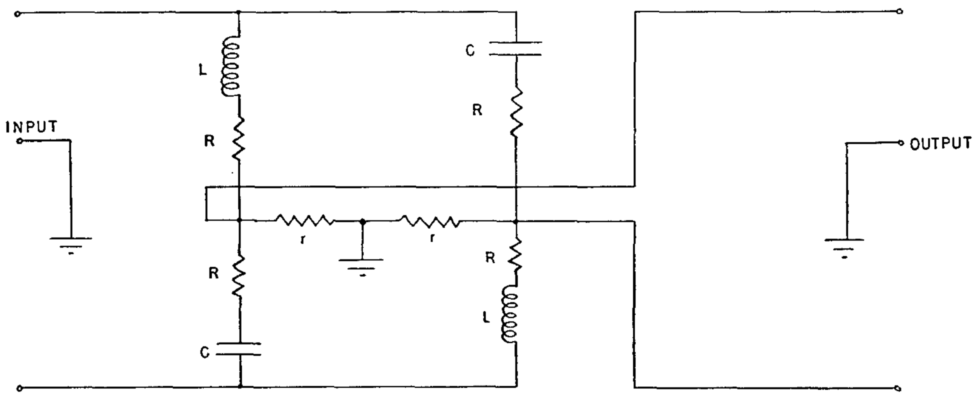


FIGURE 20. Constant phase-shift network.

calculations. However, the change in the amplitude of the output with frequency is more serious. In an octave centered about the resonant frequency the output unbalance reaches about 2 db. This unbalance should not seriously affect the BDI bearing accuracy, however.

The accuracy with which the components must be specified is probably greater with the circuit of Figure 20 than with the usual BDI lag line, because the two BDI channels are essentially separate parts of the network and must be approximately balanced, whereas the standard lag line enters symmetrically into the two BDI channels.

The network has no center tap to which the standard receiver can be connected. Here, too, the absence of center tap makes it necessary to connect to the center point of a pair of resistors bridging the two channels. The resistors should be high compared with the impedance at the point of connection. There are advantages to this mode of connection; for example, if the connection were made directly across the transducer, the standard receiver would be virtually independent of the BDI receiver.

This study can be extended to various combinations of lead and lag lines to cover a wide frequency range.[12] It is found that as the number of elements is increased, the performance is improved, but the number of elements soon becomes excessive.

CONSTANT-RESISTANCE CIRCUIT

The simple low-pass, constant-K, π-section filter used in the Model X-3 BDI suffered from the disadvantage that its image impedance varied with frequency. Except at the design frequency, this resulted in an amplitude unbalance at the output of the network, which reduced the sensitivity of the BDI and which combined with input unbalance to produce a bearing error.

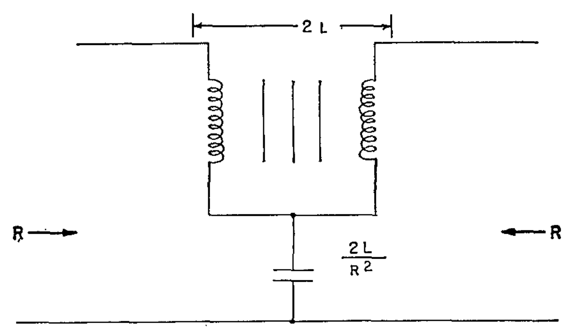


FIGURE 21. Constant resistance lag line.

It is possible to construct an all-pass section whose image impedances are constant resistances and which have better phase-shift characteristics than the constant-K, low-pass section. Such a section is shown in Figure 21.

The phase characteristics of the constant-resistance section are shown in Figure 22. For comparison, corresponding curves are also given for the constant-K π-section.

The advantages of the constant-resistance over the constant-K network decreases as the phase shift used is diminished, since for shorter sections the curves become more nearly linear with frequency and the image resistance of the constant-K section becomes less variable. For example, the ratio of the two slopes at the crossover is $\cos^2 B_0/2$, where B_0 is the phase

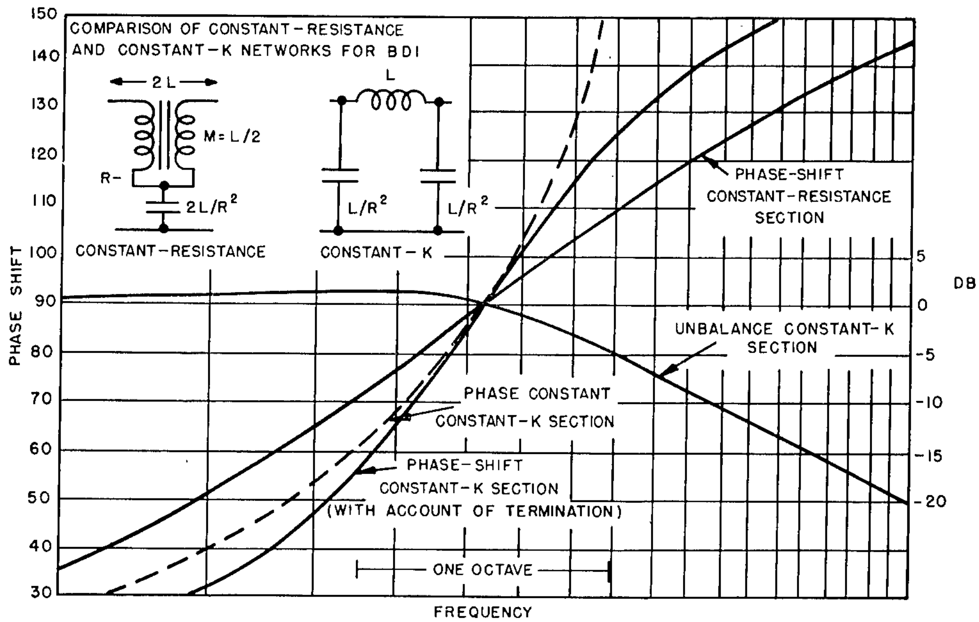


FIGURE 22. Comparison of network characteristics.

shift at this point. Thus, for 60-degree sections the ratio is ¼, instead of ½ for the 90-degree sections shown in Figure 22.

The total inductance required for the constant-resistance network when $B_0 = 90$ degrees is twice the inductance used in the constant-K network, whereas the total capacity is the same. For other values of B_0, the inductance ratio is $\sec^2 (B_0/2)$.

5.4 DEVELOPMENT

5.4.1 General BDI Experimentation

Early proposals[13,14] for applying the principle of overlapping lobes in echo ranging included a variety of approaches to the problem. One contemplated two beams used alternately, giving a separation in time, the technique of "lobe switching" as used in radar. Others involved the use of beams having slightly different carrier frequencies, or beams having identifying modulation impressed on the carriers and, finally, the system eventually used in the BDI which employs simultaneous overlapping lobes on the same frequency. The desirability of using cathode-ray screen presentation to aid in visual discrimination against noise was recognized at an early date.

At first the use of continuous transmission and reception of sound, as well as of pulse transmissions, was considered. Actual echo-ranging work by members of HUSL, however, led to the design embodied in the Model X-1 BDI, specifying manually-trained azimuth measuring gear, using as much as possible of Submarine Signal Company (QC) equipment, but incorporating the principle of overlapping lobes for better accuracy and ease of manipulation.

5.4.2 Model X-1 BDI

In Model X-1 a single-channel heterodyne amplifier was used to give simultaneous amplification of two intermediate frequencies. This made it possible to apply manual and TVG control to both right and left channels without introducing relative unbalance. In this model, too, the magnetic deflection cathode-ray tube was first used and gave considerable improvement in the visual presentation, since the long persistence of the P7 phosphor was ideally adapted to the time scale of echo-ranging operations. The AVC circuit is not true AVC but an adaptation to BDI of TVG (see Section 2.2), also referred to occasionally as *time-controlled gain* [TCG].

5.4.3 Model X-2 BDI

Following satisfactory testing of the first BDI (or SLC) unit, eight more were constructed. Although these units were almost identical with the first model in external appearance, they incorporated enough circuit modification to warrant designating them as Model X-2.

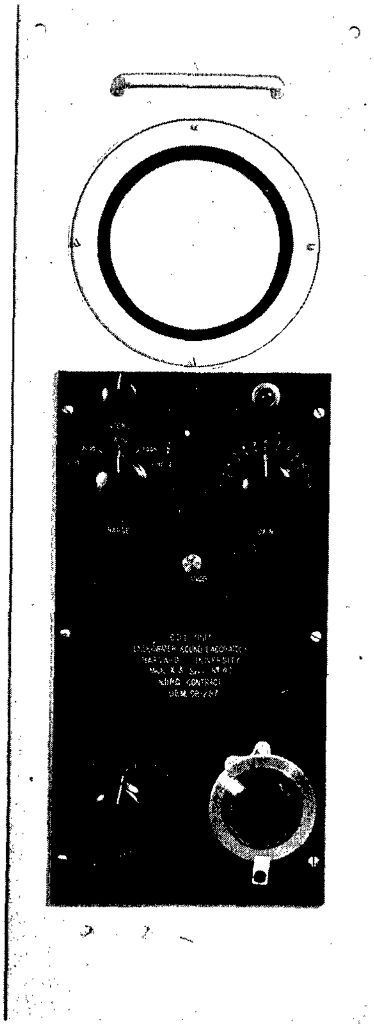


FIGURE 23. Close-up of Model X-3 BDI.

5.5 MODEL X-3 BDI

Experience gained during the development and testing of Models X-1 and X-2 led to the design of Model X-3 BDI (Figure 23) which is more compact and has all the circuits contained in one chassis. Model X-3 also includes the noise sweep. In the earlier units when BDI was used for listening, the spot oscillated about a point in the center of the screen and tended to burn a hole at that point.

A special modification of BDI Model X-3, known as Model X-3A, was developed for attachment to WEA-1 sonar equipment, which has no send-receive relay.[15]

5.5.1 Circuit Analysis

Figure 24 is a block diagram and Figure 25 is a schematic diagram of the Model X-3 BDI circuit. The signal (echo) inputs from the two halves of the projector are applied to the respective input transformers. Before reaching the lag line, the signals go through an input amplifier stage, after which the phase difference between them is converted by the lag line into an amplitude difference in the manner previously explained. Thus, the signal applied to one of the mixers becomes a right-sensitive signal and that applied to the other, a left-sensitive signal.

Local signals of two difference frequencies are used in the mixer tubes to reduce the right-sensitive and left-sensitive signal frequencies to 10 and 7 kc respectively, to permit simultaneous amplification in the common-channel intermediate-frequency amplifier. All gain control is applied to the i-f amplifier so that the relative amplitudes of the signals remain constant.

After passing through the i-f amplifier, the 10- and 7-kc signals are again separated and amplified individually before they are applied to a comparison rectifier. The purpose of this comparison rectifier is to convert the 10-kc signal into a positive d-c voltage and the 7-kc signal into a negative voltage, and then to compare the two. If the 10-kc signal has a greater amplitude than the 7-kc signal, the positive voltage produced by rectification of the former exceeds the negative voltage produced by rectification of the latter, and the output of the comparison rectifier is a positive voltage. Con-

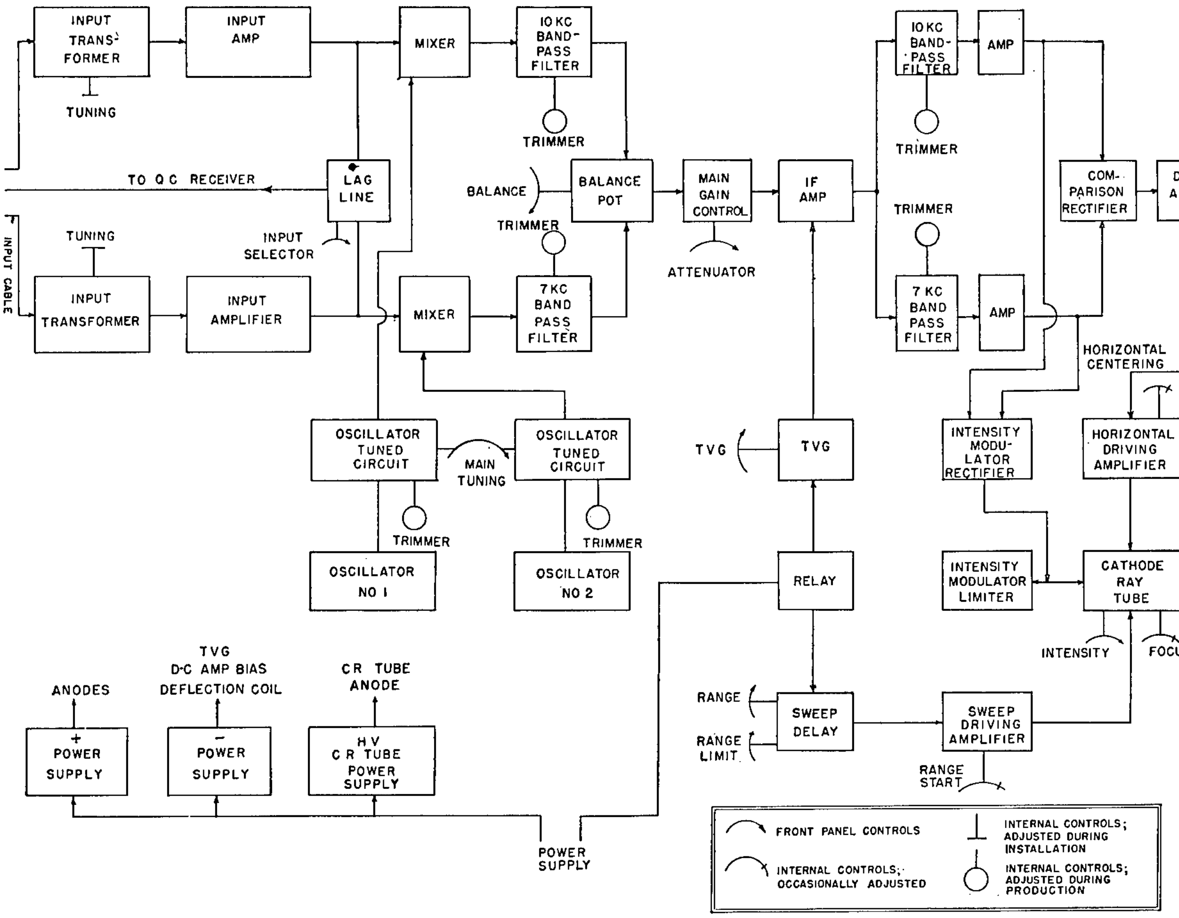


FIGURE 24. Block diagram of Model X-3 BDI circuit.

versely, if the 7-kc signal exceeds the 10-kc signal in magnitude the output is negative. The magnitude of the d-c output voltage of the comparison rectifier is proportional to the difference in amplitude of the 10- and 7-kc signals applied to it.

The output of the comparison rectifier controls the output of the horizontal deflecting circuit of the cathode-ray tube. A positive voltage applied to this control circuit (which includes the d-c amplifier and horizontal deflection amplifier) causes the trace on the cathode-ray tube screen to move to the right, while a negative voltage causes it to move to the left.

From this explanation it can be seen that an echo coming from a direction either to the right or to the left of the projector bearing produces a visual indication by causing the trace on the screen of the cathode-ray tube to deflect in the direction from which the echo is received, and brightening of the trace occurs. The visual indication takes place simultaneously with the audible reception of the echo on the sonar receiver.

When an echo arriving along the axis of the projector is received, no deflection of the trace is produced because the output of the comparison rectifier is zero. However, a positive indication of the presence of the echo is produced simultaneously with the reception of the audible echo by the brightening circuit which causes the trace to become more brilliant for the duration of the echo.

5.6 MODEL X-4 BDI

As experience accumulated, it became evident that, although the units performed according to specifications, certain features could profitably

be simplified both to make it easier to maintain the units at peak efficiency and to simplify commercial construction. The tuned circuit components of the X-3 BDI, in particular, were thought to be logical objects for further development aimed at increasing the tolerances allowable in their alignment.

5.6.1 General Description

The X-4 BDI looks much the same as the X-3 externally. Its component circuits are different, however. All the differences make for wider tolerances permissible in manufacture and hence simplify the commercial production of BDI's. The shipboard installation of the units is also simplified.

Model X-4 was designed to meet the various performance specifications of Model X-3.[16] In the circuit of Model X-4 a common amplifier is utilized for most of the amplification of the signals delivered from the two sides of the BDI lag line. Directionality information is carried through this amplifier by means of local modulation impressed upon the carrier frequency. After amplification, a detector which is sensitive to the phase of the modulation is used to produce right-left deflections on the oscilloscope.

Model X-4 of the bearing deviation indicator contains only two band-pass filters (instead of the four needed in the X-3 model) both tuned to the same frequency. Accordingly, the i-f alignment is considerably simplified because the information from both input channels is carried through the same circuit components. Also, only one superheterodyne oscillator is employed; hence, the oscillator tracking problem found in the X-3 model does not exist in the X-4.

A signal, once inserted into the single channel amplifier of Model X-4 is not split again into two channels. If any distortion occurs, both channels are treated similarly, and no error in the center indication is introduced. This is not the case in the Model X-3 receiver, where the two channels are split in the output before rectification.

The use of a high intermediate frequency in

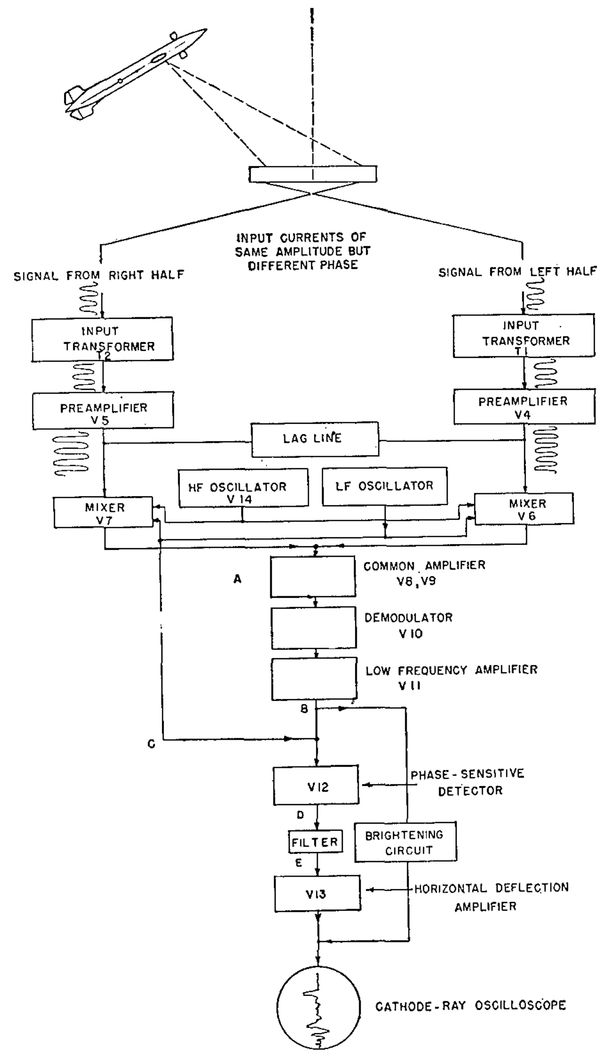


FIGURE 26. Simplified block diagram of X-4 BDI.

Model X-4 makes possible the use of untuned, or broadly tuned, input transformers, whereas the X-3 model requires tuned input transformers whose tuning has to be matched very closely, and maintained to this close match.

5.6.2 Circuit Analysis

Figure 26 is a simplified block diagram of the X-4 type of BDI. Currents from the two projector halves flow through the untuned input transformers T-1 and T-2 and are applied to the two preamplier stages V-4 and V-5. A lag line connecting both preamplifiers translates the varying phases of projector currents

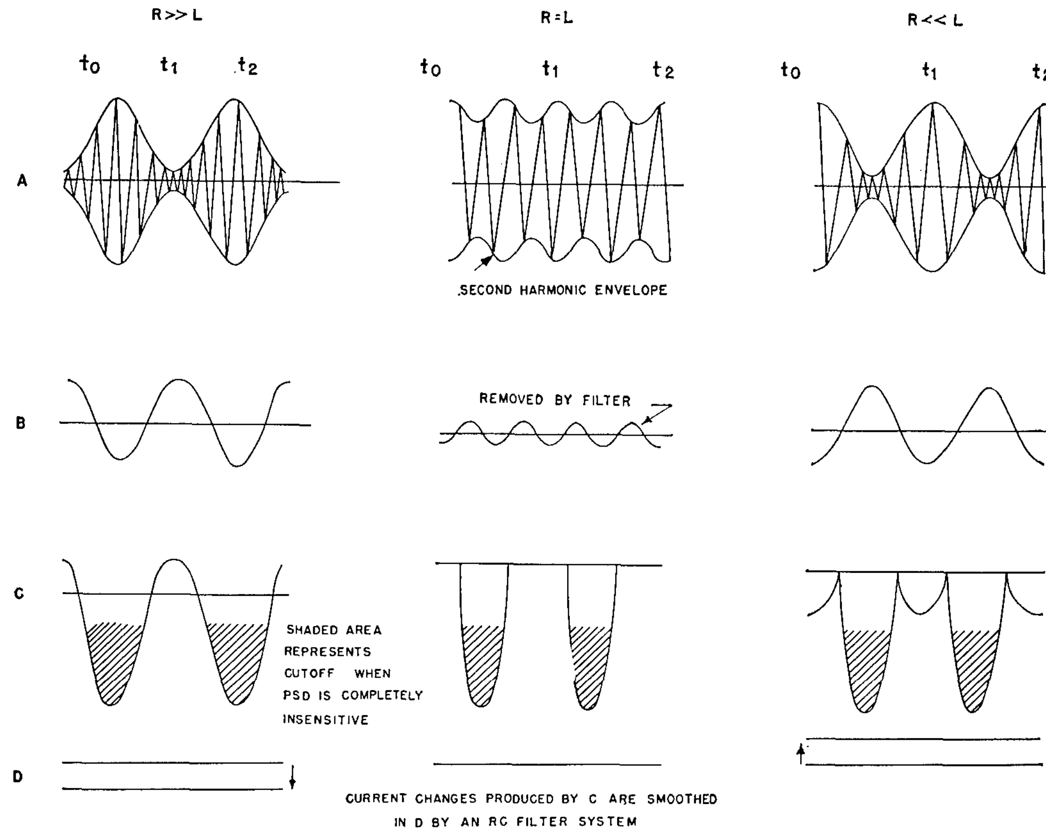


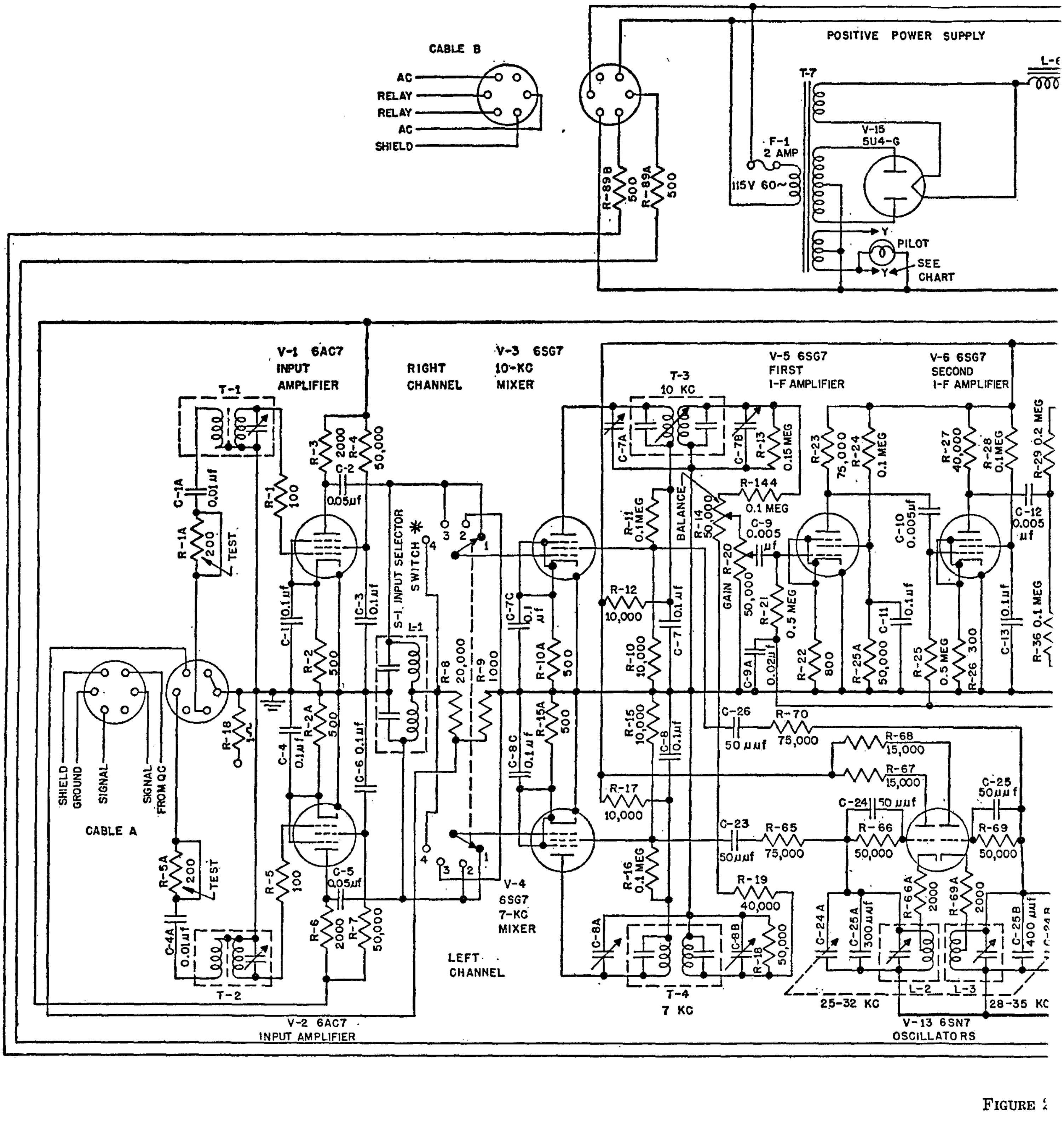
FIGURE 27. Signal at various points in X-4 BDI.

into varying amplitudes which are compared to provide right and left indications. The right and the left projector lobes are applied to a mixer-switching stage (V-6 and V-7). Simultaneous injection of a high-frequency signal (near 80 kc) generated by one section of V-14 produces a 60-kc difference frequency which is amplified in the common amplifier V-8 and V-9.

In addition to the mixing action, V-6 and V-7 serve as switches operated by the low-frequency section of V-14. The electronic switching, at a rate of about 400 c, alternately connects the 60-kc common amplifier to the right and left projector lobes. This permits comparison, later in the circuit, of the absolute levels of signal delivered by the two lobes.

In Figure 27 are shown the envelopes of the signals at the various stages in the BDI designated by the corresponding letter in Figure 26. Figure 27A illustrates the shape of the carrier envelope in the common amplifier when equal signals are delivered by the right and left lobes and when unequal signals are produced. It can be seen that the minimum of the modulation envelope occurs at a relative time t_1 when the right lobe is stronger while maximum modulation is had at t_1 when the left lobe is stronger. When equal signals are delivered by each lobe, no switching fundamental modulation envelope exists. Therefore, a system has been provided which will indicate right and left signals, in which the amount of right or left deflection is determined by the depth of modulation in the common channel.

One half of V-10 serves a function similar to that of a second detector in a superheterodyne radio. This detector supplies signals to the low-frequency amplifier V-11, the output of which is shown in Figure 27B. It should be noted that this action has discarded the high-frequency 60-kc carrier but kept the modula-



CABLE B
AC
RELAY
RELAY
AC
SHIELD
POSITIVE POWER SUPPLY
T-7
V-15
5U4-G
F-1
2 AMP
115V 60~
PILOT
SEE CHART
R-89B
500
R-89A
500
V-1 6AC7
INPUT AMPLIFIER
RIGHT CHANNEL
V-3 6SG7
10-KC MIXER
V-5 6SG7
FIRST
I-F AMPLIFIER
V-6 6SG7
SECOND
I-F AMPLIFIER
T-1
T-3
10 KC
S-1 INPUT SELECTOR SWITCH
BALANCE
GAIN
TEST
CABLE A
SHIELD
GROUND
SIGNAL
SIGNAL FROM QC
V-4
6SG7
7-KC MIXER
LEFT CHANNEL
T-2
T-4
7 KC
25-32 KC
28-35 KC
V-2 6AC7
INPUT AMPLIFIER
V-13 6SN7
OSCILLATORS

FIGURE

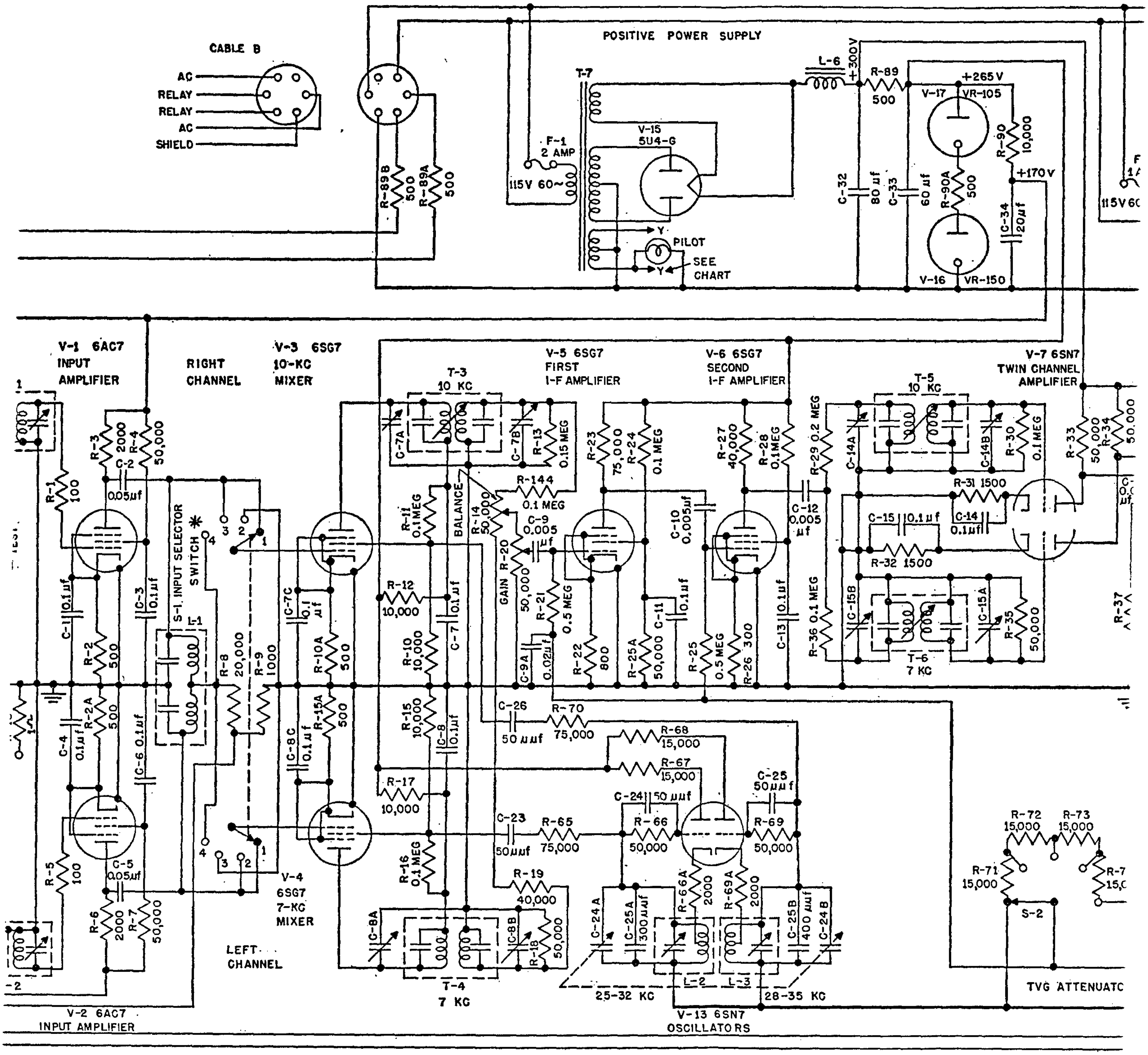


FIGURE 25. Circuit diagram of Model X-3 BD

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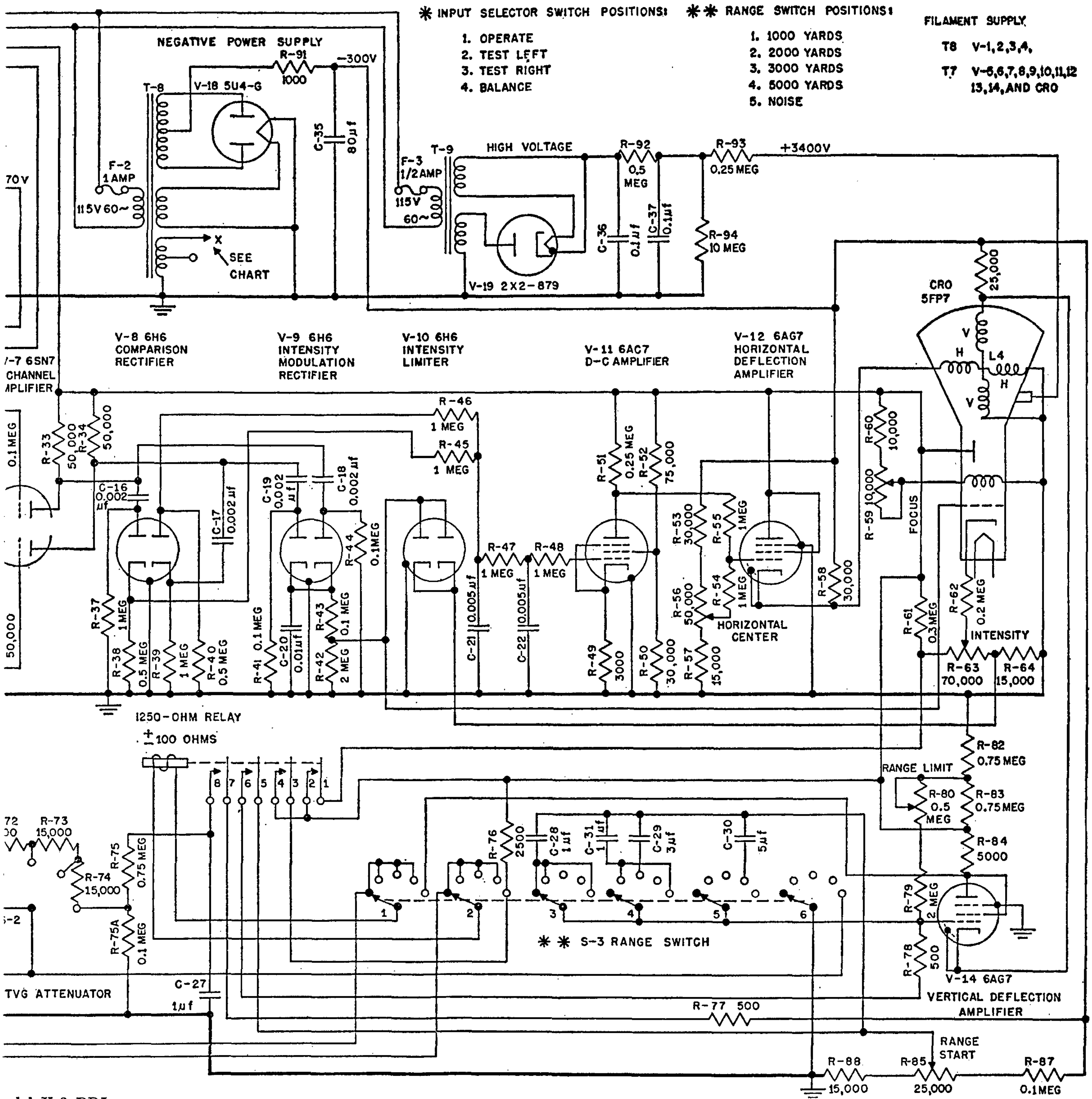

✱ INPUT SELECTOR SWITCH POSITIONS:
1. OPERATE
2. TEST LEFT
3. TEST RIGHT
4. BALANCE
✱✱ RANGE SWITCH POSITIONS:
1. 1000 YARDS
2. 2000 YARDS
3. 3000 YARDS
4. 5000 YARDS
5. NOISE
FILAMENT SUPPLY
T8 V-1,2,3,4.
T7 V-5,6,7,8,9,10,11,12 13,14,AND CRO
NEGATIVE POWER SUPPLY
R-91 1000
-300V
T-8
V-18 5U4-G
C-35 80μf
F-2 1 AMP
115V 60~
SEE CHART
HIGH VOLTAGE
T-9
F-3 1/2 AMP
115V 60~
V-19 2X2-879
R-92 0.5 MEG
R-93 0.25 MEG
+3400V
C-36 0.1μf
C-37 0.1μf
R-94 10 MEG
CRO 5FP7
25,000
V-8 6H6 COMPARISON RECTIFIER
V-9 6H6 INTENSITY MODULATION RECTIFIER
V-10 6H6 INTENSITY LIMITER
V-11 6AC7 D-C AMPLIFIER
V-12 6AG7 HORIZONTAL DEFLECTION AMPLIFIER
V-7 6SN7 CHANNEL AMPLIFIER
R-46 1 MEG
R-45 1 MEG
R-33 50,000
R-34 50,000
C-16 0.002μf
C-17 0.002μf
C-19 0.002μf
C-18 0.002μf
R-44 0.1MEG
R-47 1 MEG
R-48 1 MEG
R-51 0.25 MEG
R-52 75,000
R-53 30,000
R-55 1MEG
R-54 1MEG
R-56 50,000
HORIZONTAL CENTER
R-58 30,000
R-60 10,000
R-59 10,000
FOCUS
R-37 1MEG
R-38 0.5 MEG
R-39 1 MEG
R-40 0.5 MEG
R-41 0.1 MEG
C-20 0.01μf
R-43 0.1 MEG
R-42 2 MEG
C-21 0.005μf
C-22 0.005μf
R-49 3000
R-50 30,000
R-57 15,000
R-61 0.3MEG
R-62 0.2 MEG
INTENSITY
R-63 70,000
R-64 15,000
1250-OHM RELAY
±100 OHMS
R-82 0.75 MEG
RANGE LIMIT
R-80 0.5 MEG
R-83 0.75MEG
R-84 5000
R-76 2500
C-28 1μf
C-31 1μf
C-29 3μf
C-30 5μf
R-73 15,000
R-74 15,000
R-75 0.75 MEG
R-75A 0.1 MEG
✱✱ S-3 RANGE SWITCH
R-79 2 MEG
R-78 500
V-14 6AG7 VERTICAL DEFLECTION AMPLIFIER
TVG ATTENUATOR
C-27 1μf
R-77 500
RANGE START
R-88 15,000
R-85 25,000
R-87 0.1MEG

odel X-3 BDI.

3

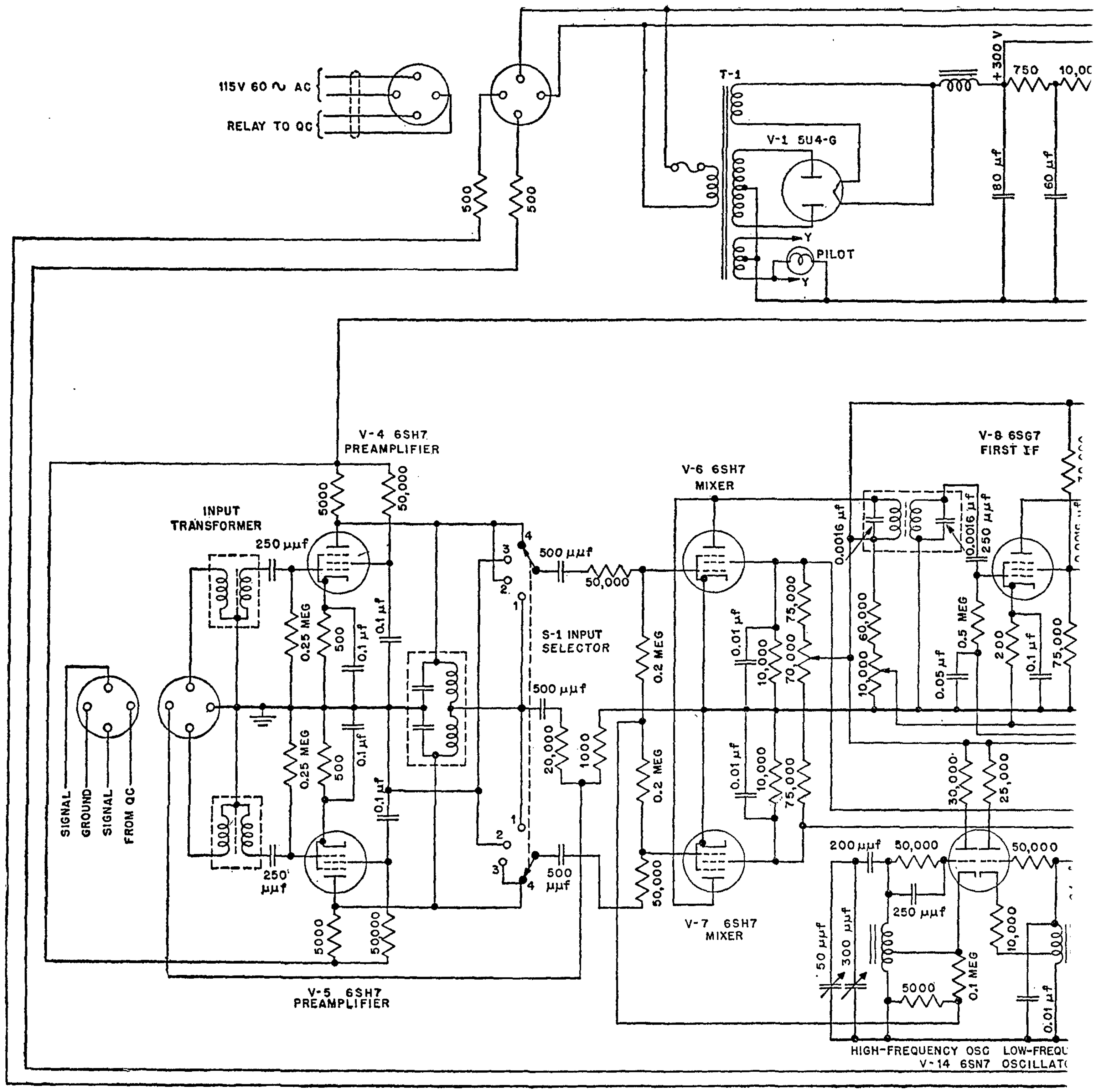
115V 60 ~ AC
RELAY TO QC
T-1
V-1 5U4-G
PILOT
+300 V
750
80 μf
60 μf
V-4 6SH7
PREAMPLIFIER
INPUT
TRANSFORMER
250 μμf
S-1 INPUT
SELECTOR
500 μμf
V-6 6SH7
MIXER
V-7 6SH7
MIXER
V-8 6SG7
FIRST IF
V-5 6SH7
PREAMPLIFIER
SIGNAL
GROUND
SIGNAL
FROM QC
HIGH-FREQUENCY OSC
V-14 6SN7

FIGURE 28.

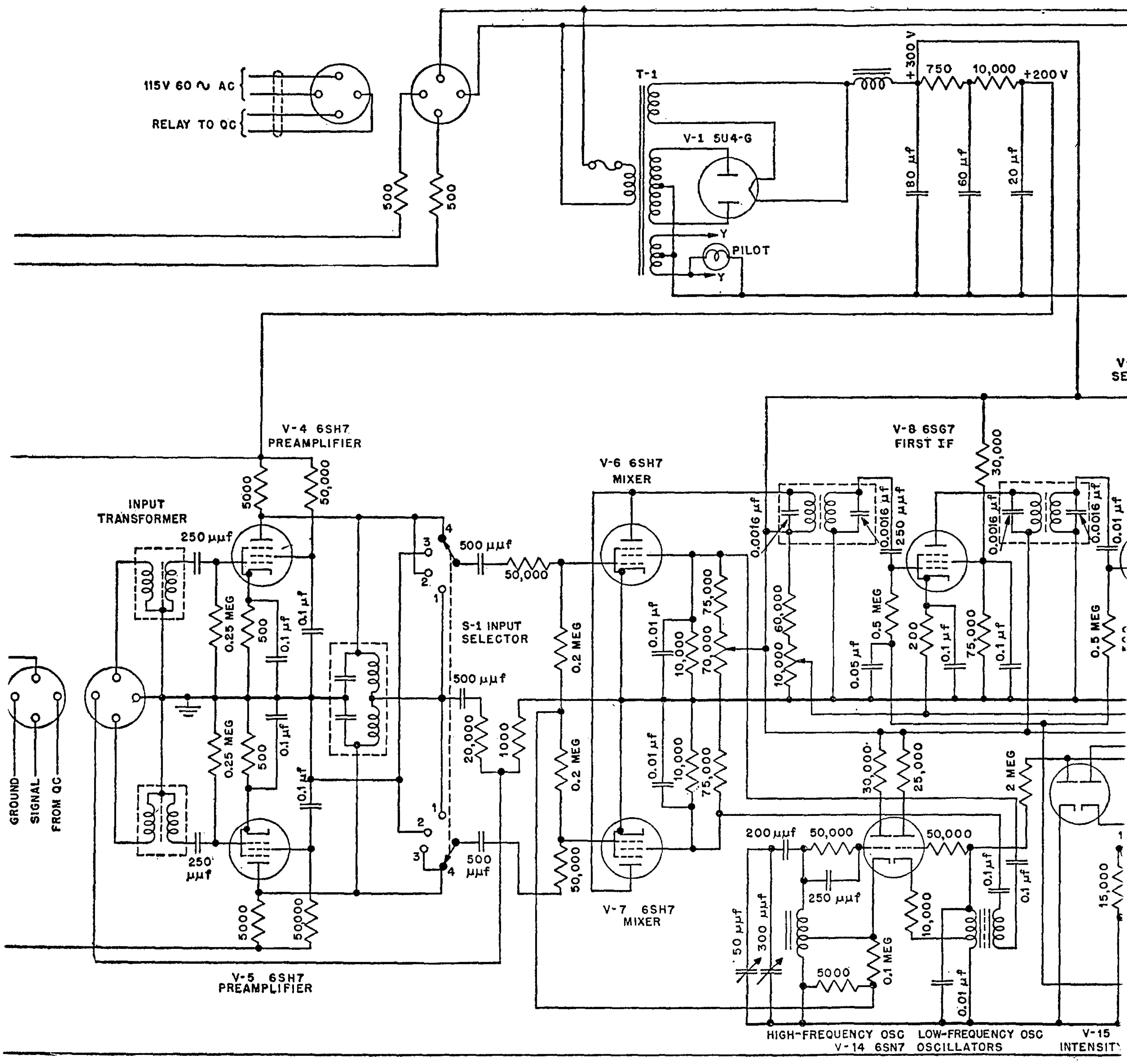

FIGURE 28. Circuit diagram o:

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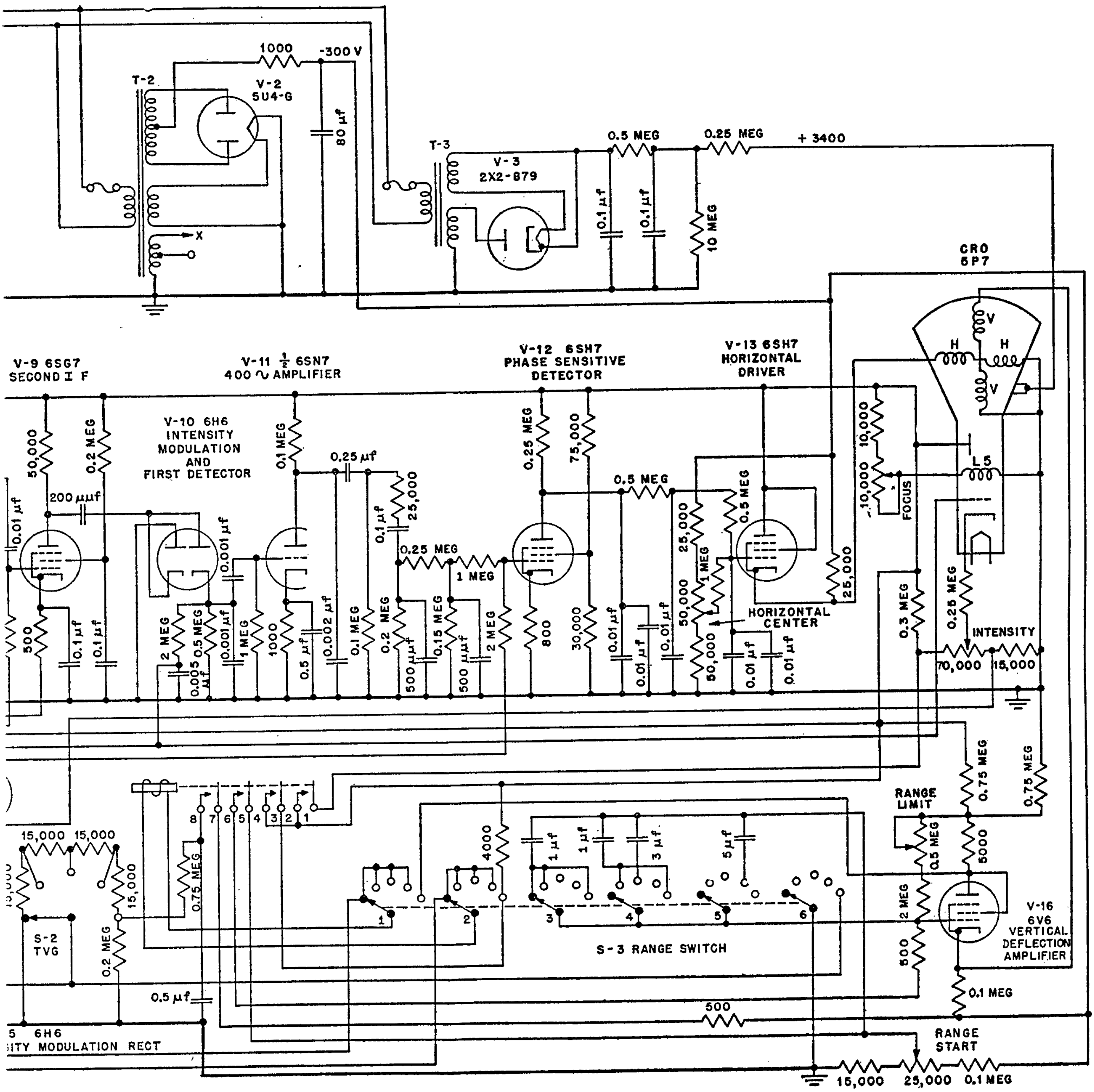

of X-4B BDI.

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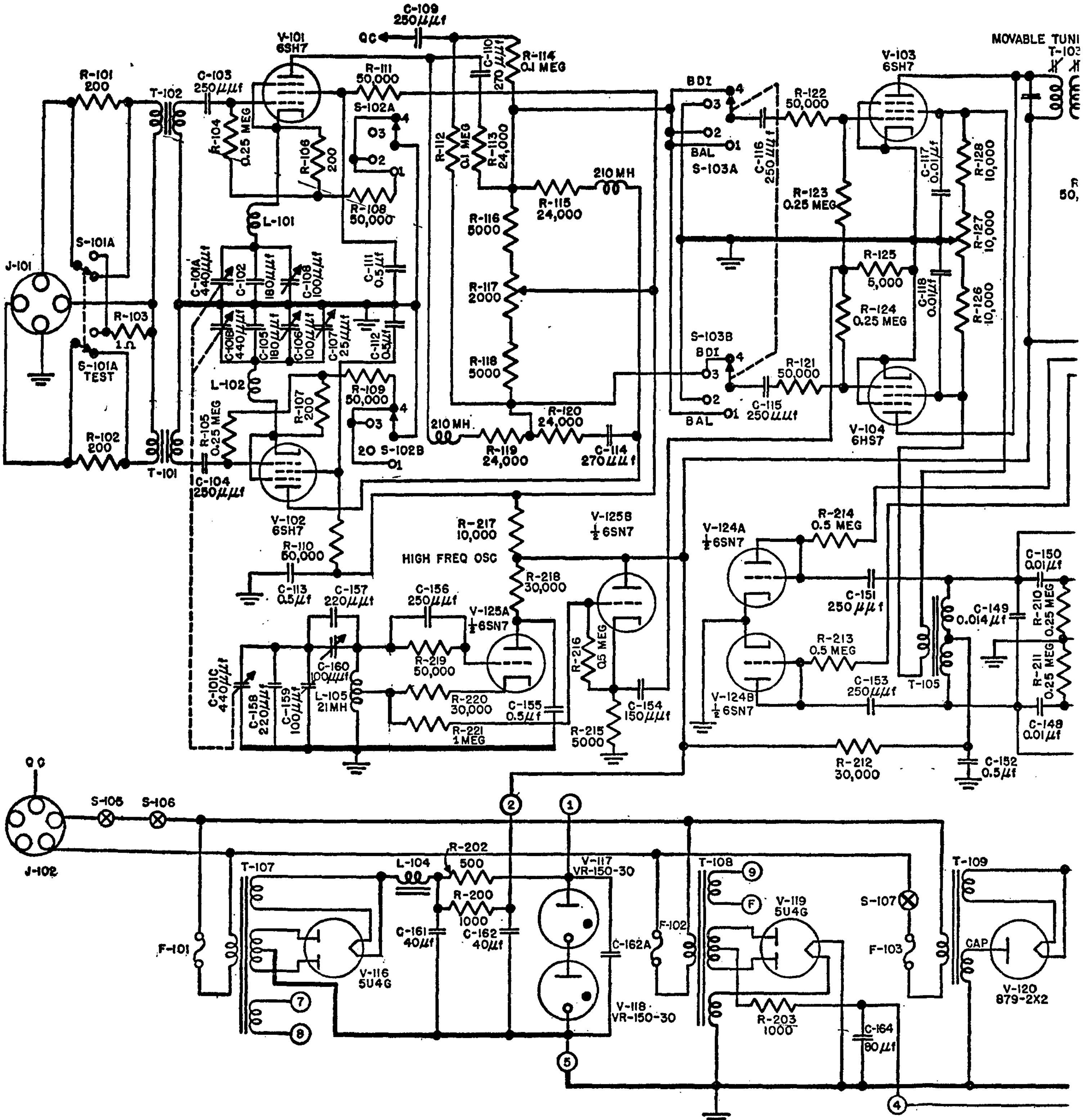

C-109
250μμf
QC
V-101
6SH7
R-111
50,000
R-114
0.1 MEG
C-110
270μμf
MOVABLE TUNI
T-103
V-103
6SH7
R-101
200
T-102
C-103
250μμf
S-102A
BDI
BAL
S-103A
R-122
50,000
R-104
0.25 MEG
R-106
200
R-112
0.1 MEG
R-113
24,000
C-116
250μμf
C-117
0.01μf
R-128
10,000
R-108
50,000
R-115
24,000
210 MH
R-123
0.25 MEG
L-101
R-116
5000
R-127
10,000
S-101A
J-101
C-101A
440μμf
C-102
180μμf
C-108
100μμf
C-111
0.5μf
R-125
5,000
R-117
2000
C-118
0.01μf
R-126
10,000
R-124
0.25 MEG
R-103
1Ω
C-101B
440μμf
C-105
180μμf
C-106
100μμf
C-107
25μμf
C-112
0.5μf
S-101A
TEST
S-103B
L-102
R-118
5000
R-121
50,000
R-107
200
R-109
50,000
R-105
0.25 MEG
R-120
24,000
C-115
250μμf
S-102B
V-104
6HS7
R-102
200
T-101
C-104
250μμf
R-119
24,000
C-114
270μμf
V-102
6SH7
R-217
10,000
V-125B
½ 6SN7
V-124A
½ 6SN7
R-214
0.5 MEG
R-110
50,000
HIGH FREQ OSC
C-150
0.01μf
C-113
0.5μf
C-157
220μμf
C-156
250μμf
R-218
30,000
C-151
250 μμf
C-149
0.014μf
R-210
0.25 MEG
V-125A
½ 6SN7
R-219
50,000
C-160
100μμf
R-216
0.5 MEG
R-213
0.5 MEG
C-101C
440μμf
C-158
220μμf
C-159
100μμf
L-105
21MH
R-220
30,000
C-155
0.5μf
C-154
150μμf
C-153
250μμf
T-105
R-211
0.25 MEG
R-221
1 MEG
R-215
5000
V-124B
½ 6SN7
C-148
0.01μf
R-212
30,000
C-152
0.5μf
QC
S-105
S-106
J-102
R-202
500
T-107
L-104
R-200
1000
V-117
VR-150-30
T-108
S-107
T-109
F-101
C-161
40μf
C-162
40μf
C-162A
F-102
V-119
5U4G
F-103
CAP
V-116
5U4G
V-118
VR-150-30
R-203
1000
C-164
80μf
V-120
879-2X2

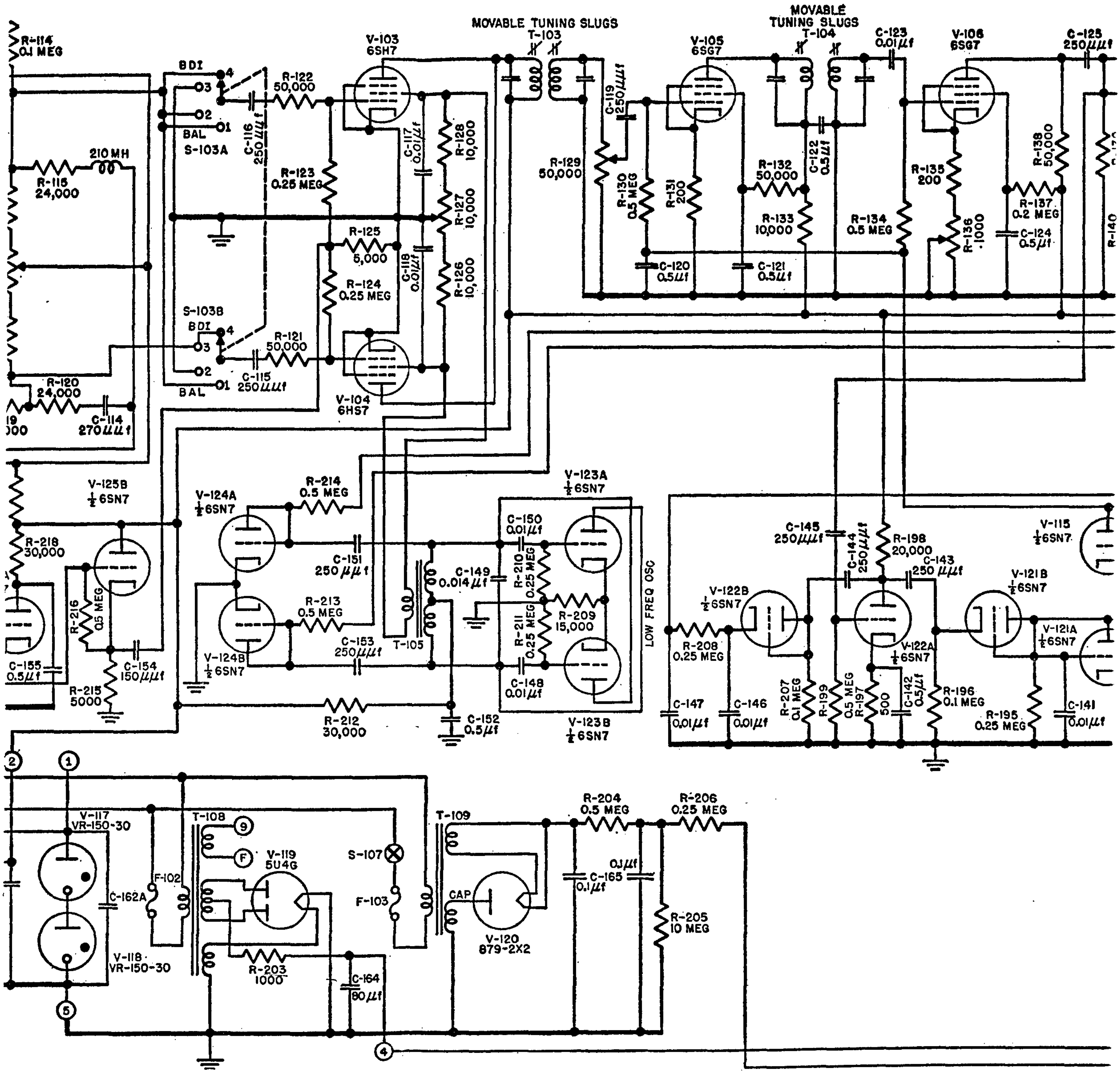

FIGURE 29. Circuit diagram of X-4D BDI.

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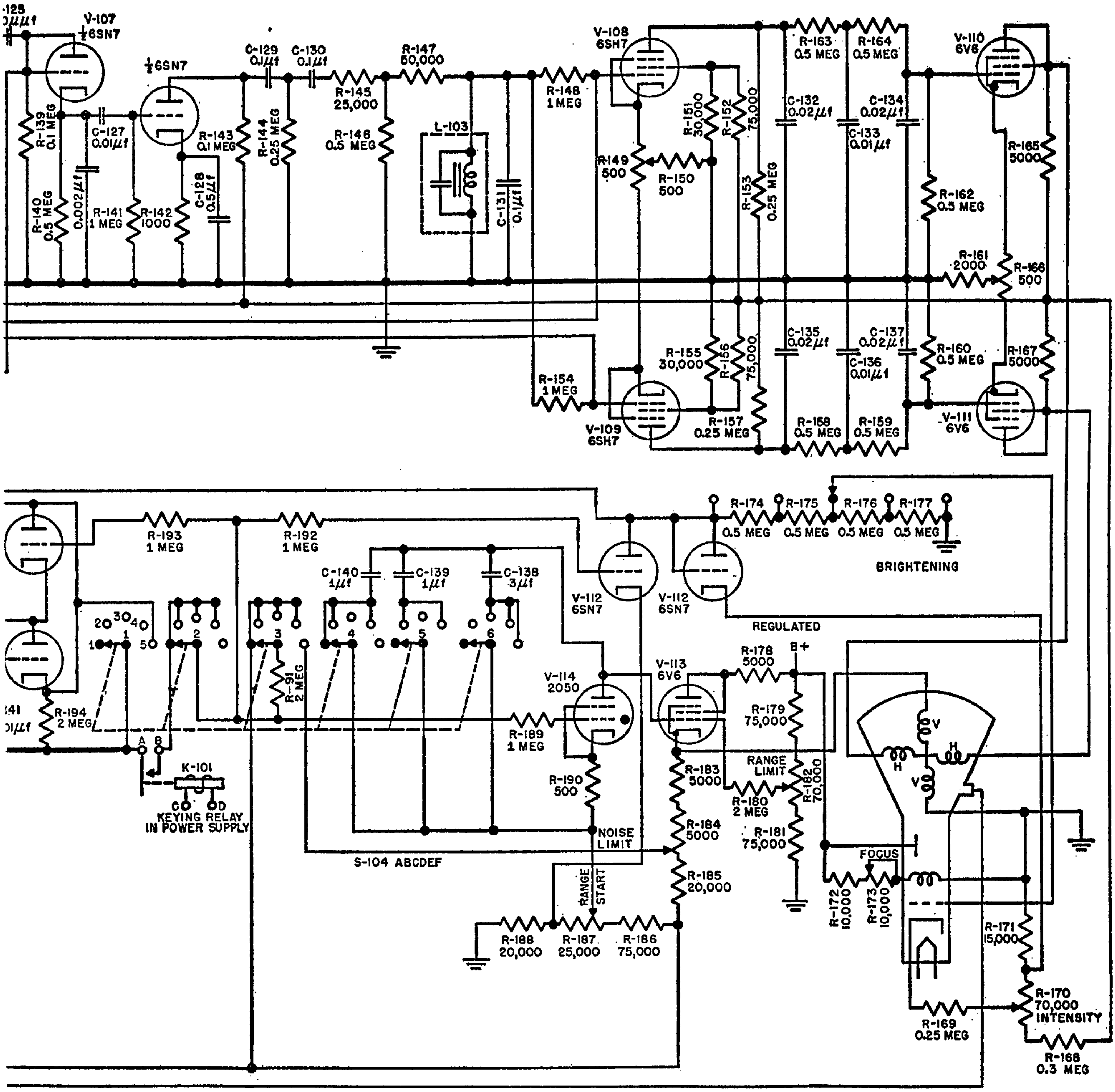

V-107
½6SN7
½6SN7
C-129
0.1µf
C-130
0.1µf
R-147
50,000
V-108
6SH7
R-163
0.5 MEG
R-164
0.5 MEG
V-110
6V6
R-139
0.1 MEG
C-127
0.01µf
R-143
0.1 MEG
R-144
0.25 MEG
R-145
25,000
R-146
0.5 MEG
L-103
R-148
1 MEG
R-151
30,000
R-152
75,000
C-132
0.02µf
C-134
0.02µf
C-133
0.01µf
R-165
5000
R-140
0.5 MEG
0.002µf
R-141
1 MEG
R-142
1000
C-128
0.5µf
C-131
0.1µf
R-149
500
R-150
500
R-153
0.25 MEG
R-162
0.5 MEG
R-161
2000
R-166
500
R-155
30,000
R-156
75,000
C-135
0.02µf
C-137
0.02µf
C-136
0.01µf
R-160
0.5 MEG
R-167
5000
R-154
1 MEG
V-109
6SH7
R-157
0.25 MEG
R-158
0.5 MEG
R-159
0.5 MEG
V-111
6V6
R-174
R-175
R-176
R-177
0.5 MEG
0.5 MEG
0.5 MEG
0.5 MEG
BRIGHTENING
R-193
1 MEG
R-192
1 MEG
C-140
1µf
C-139
1µf
C-138
3µf
V-112
6SN7
V-112
6SN7
REGULATED
R-178
5000
B+
V-114
2050
V-113
6V6
R-179
75,000
R-91
2 MEG
R-194
2 MEG
R-189
1 MEG
RANGE
LIMIT
R-182
70,000
V
H
H
V
K-101
KEYING RELAY
IN POWER SUPPLY
R-190
500
R-183
5000
R-180
2 MEG
R-181
75,000
NOISE
LIMIT
R-184
5000
S-104 ABCDEF
FOCUS
R-185
20,000
RANGE
START
R-172
10,000
R-173
10,000
R-171
15,000
R-188
20,000
R-187
25,000
R-186
75,000
R-170
70,000
INTENSITY
R-169
0.25 MEG
R-168
0.3 MEG

tion, thus preserving the proper information for bearing deviation indication. With a balanced signal coming directly along the axis of the projector, no 400-c signal is applied to V-11, while right and left signals produce a 400-c voltage which reverses phase as the bearing passes through zero. A 400-c filter serves to remove undesired harmonic components which are the result of switching in V-6 and V-7. The purified 400-c voltage is then applied to the phase-sensitive detector, V-12. A reference signal from the low-frequency oscillator is also injected into this stage with wave forms as shown in Figure 27C. This tube is arranged to provide an increase in average plate current with one phase of 400 c from the receiver amplifier and a decrease of plate current with the other phase. Thus, plate current will increase if a signal is received from the right of the projector bearing and decrease if a signal is received from the left (Figure 27D). This stage is direct-coupled to the horizontal deflection amplifier.

In order that the oscilloscope shall indicate average current in the phase-sensitive detector rather than the instantaneous changes resulting from the continuous switching, the detector output is applied to the deflection amplifier stage through a low-pass filter system which effectively removes the 400-c switching ripple, but permits relatively rapid changes in average current to be indicated. The resultant trace on a CRO screen therefore does not show any deflection caused by the switching signal.

One half of V-10 and one half of V-15 are used in the brightening circuits to increase the brilliancy of the CRO trace when an echo is received.

Model X-4D BDI

The foregoing explanations referred to the basic X-4 circuit (shown in Figure 28), which came to be known as Model X-4B. A further modification of the circuit (called X-4D) is shown in Figure 29. The basic idea was the same in both models, but the method of accomplishing certain of the results differed. These differences are explained fully in reference 1.

X-4 Versus X-3 BDI

The X-4 unit was tested over a considerable period of time, with satisfactory results. In general, the indications furnished by Model X-4 were identical with those furnished by Model X-3. When both models were operated simultaneously from the same projector, the traces were frequently almost identical. The Model X-4 receiver was slightly more sensitive to undesired noise than the Model X-3, but this increased noise sensitivity amounted only to about 2 db and tests indicated that the effect would not be serious. By using tuned input transformers the signal-to-noise ratio could be made essentially identical for the two models.

The CRO indications of the X-4 when listening to hydrophone effect were still inferior to the X-3. The deflections became a minimum when the X-4 was trained on bearing, but could not be brought to zero deflection, as was possible with the X-3 model. This slight advantage in performance on noise which the X-3 unit shows over the X-4 model is far outweighed, however, by the greater ease of construction, installation, and maintenance of the X-4 unit.

5.7 SUM-AND-DIFFERENCE BDI

Description

The sum-and-difference BDI receiver here described (see block diagram of Figure 30) is a preliminary model intended for operation at about 26 kc. It was designed to work out certain questions about such a system for inclusion in the integrated sonar system.[b] For this application it was intended that the BDI operate at a higher frequency of about 40 kc.

This type of BDI is advantageous when used with the scanning sonar planned for the integrated system because (1) it permits connection of the scanning and listening receivers to the projector without interaction, while allowing simplified switching to provide for the transmission period, and (2) it eliminates the use of a separate audio listening receiver, since this function can be performed by the sum

[b] See Division 6, Volume 16.

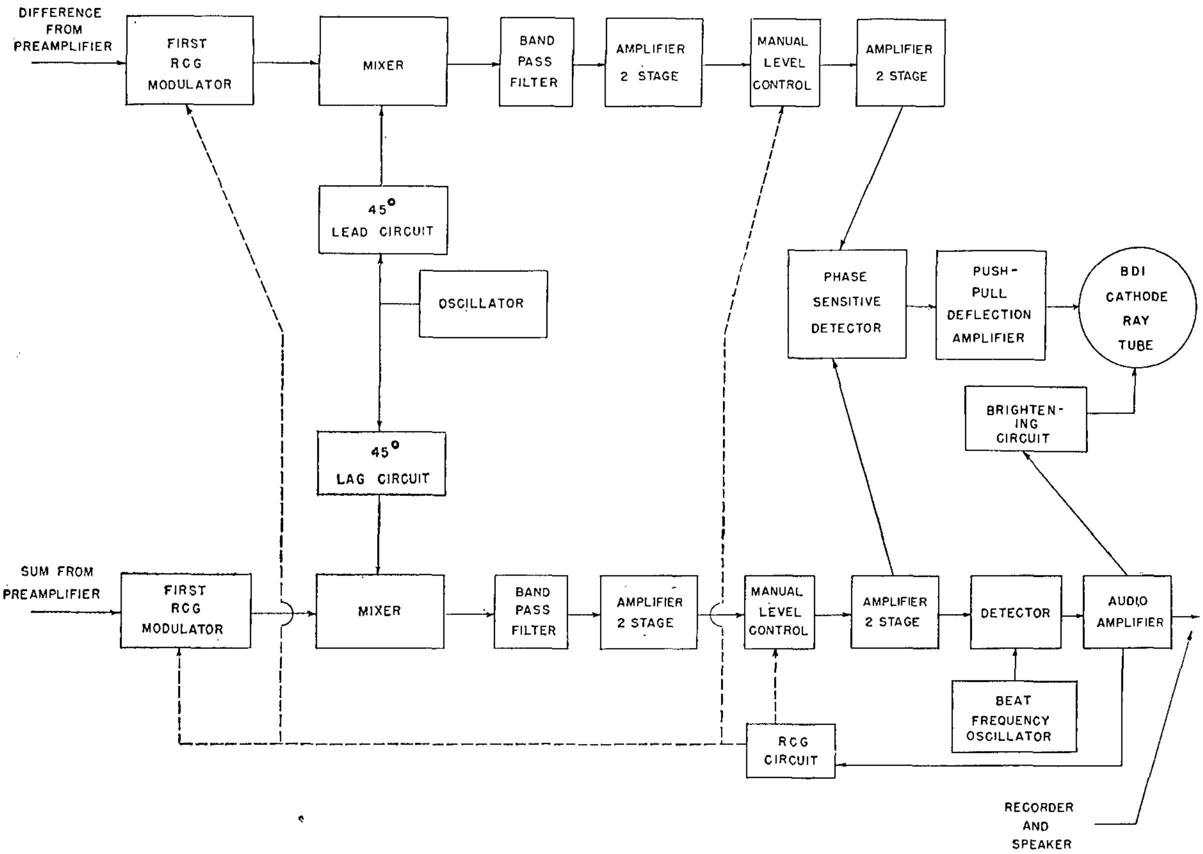


FIGURE 30. Block diagram of sum-and-difference BDI integrated system.

channel. Although a convenience, the latter advantage does not effect a saving in tubes.

Circuit Analysis

The input to the receiver comes from preamplifiers mounted on the commutators which produce the scanning. In both sum-and-difference channels the input is coupled to a varistor-balanced modulator circuit called an RCG modulator. The output of the modulator is coupled to a succeeding balanced modulator varistor circuit called the mixer where the incoming signal is combined with a local oscillator to produce the required intermediate-frequency signal. The local oscillator is coupled to the phasing circuits by means of a cathode follower.

One phasing circuit is a 45-degree lead line which is amplified and fed into the difference-channel mixer, whereas the other phasing circuit, a 45-degree lag line, is amplified and fed into the mixer in the sum channel. These phasing circuits are designed to give a 45-degree shift at the oscillator frequency. For changes in oscillator frequency of the order of one octave the phase shift of one of the elements increases as the other decreases, so that the total shift between the two channels remains close to 90 degrees.

The output of the mixer in each channel after passing through a band-pass filter is transformer-coupled into the first grid of a dual triode amplifier stage with negative feedback. The output of the amplifier in each channel goes to another varistor modulator which is used as a manual gain control. Control is obtained by applying d-c bias to the varistor by means of a potentiometer.

The output of the second modulator goes to another dual triode amplifier section in each channel. This amplifier is identical with the previous one. The two channels are then mixed in a phase-sensitive detector circuit which

feeds a d-c signal to the grids of the push-pull deflection amplifier of the CRO indicator tube.

The output of the dual triode amplifier in the sum channel is also coupled to a power detector circuit where the incoming i-f signal is mixed with a local oscillator to give a 500-c beat note for listening purposes. A single-stage triode audio amplifier, which follows, feeds the beat note to a power amplifier stage and thence to a speaker and the chemical recorder.

The output of the first stage of audio amplification is coupled to both an RCG circuit and a brightening circuit. In the RCG circuit a high signal voltage leaks into the input during the transmission period. This voltage is rectified by a triode having a fixed cathode bias so that it rectifies only signals above a certain level. The d-c output of the triode is used to charge a capacitor negatively with respect to ground. The voltage across the capacitor is applied to the grid of a triode used as a d-c amplifier. The capacitor is discharged through a triode used as a diode which is subject to a delaying bias produced by another triode used as a rectifier. The latter triode rectifies voltages produced by reverberation. Consequently, the discharge of the condenser, and therefore the gain of the receiver, is controlled by the rate of decay of reverberation.

The audio signal for the brightening of the BDI goes through an additional triode amplifying stage and then to a rectifier. The d-c output of the rectifier is amplified in a d-c amplifier-cathode follower and then is connected to a brightening limiter after which it goes to the brightening grid of the CRO tube.

5.8 SPECIAL PHASES OF BDI DEVELOPMENT

Methods of Indicating Bearing Deviation

A number of methods of indicating the deviation of a target from the projector bearing were developed at HUSL. Comparison of the relative effectiveness of these various forms of presentation gave a sound experimental basis for the adoption of the vertical-sweep-horizontal-deflection method finally used in the BDI.

Zig-Zag Indicator. The zig-zag indicator (Figure 31) appears as two parallel vertical lines on the screen of a cathode-ray tube. When only water noise is being received, these lines are short and ordinarily equal in length. When

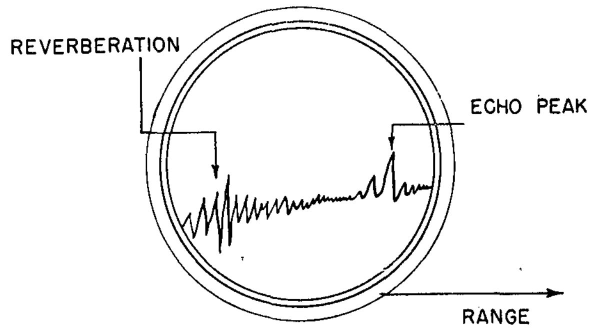


FIGURE 31. Zig-zag type of deviation indication (target to right).

an echo is received, the length of the lines increases according to the strength of the received echo. If the lines are of equal length when an echo is received, the reflecting object is on bearing. If the lines are of unequal length, the reflecting object is to the right if the right-hand line is longer; to the left if the left-hand line is longer. A left-to-right time sweep is used so that the position at which the lines appear on the screen gives an indication of range.

This indicating device was quite satisfactory under conditions where a multiplicity of echoes was not received close together. Too many echoes with small separation made it difficult to read the indication.

It was also necessary to take steps to minimize the small surges produced by the electronic switching device. Their effect is opposite on the two lines and they cause unbalance of otherwise equal indications on weak echoes.

Leaning Tower Indication. In this method of bearing deviation indication, the echo causes a single bright line to appear on the cathode-ray screen (illustrated in Figure 32). This line is perpendicular to the sweep axis if the reflecting object is on the bearing of the projector. It leans to the right if the reflecting object is to the right; left, if the left. A left-to-right time sweep is used, so that the position

at which the line appears on the screen is an indication of the range. The indicating line leans 4.4 degrees for each degree deviation between the target and the center of the receiving pattern.

The experience with this device was limited. It appeared to work satisfactorily when tested in conjunction with a sweep. It is worthy of note that the leaning tower indication method was found to be in use on German and Japanese equipment.

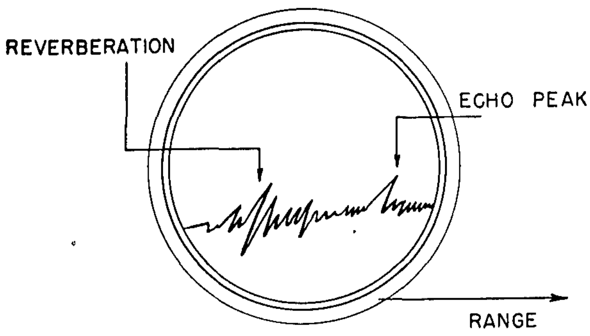


FIGURE 32. Leaning tower type of deviation indication (target to right).

Meter Indicator. A tube with a d-c meter (Figure 33) in the plate circuit is substituted for the deflection amplifier of the X-1 type. The meter, which is adjusted for a mid-scale reading in the absence of signal, indicates the right-left indications. To secure satisfactory ballistic characteristics, it is desirable to damp the meter critically and to use a discharge time constant some five times as great as for the corresponding cathode-ray indicator. In order to prevent confusion because of echoes from undesired reflecting objects and from reverberation, use of a gate circuit is found desirable.

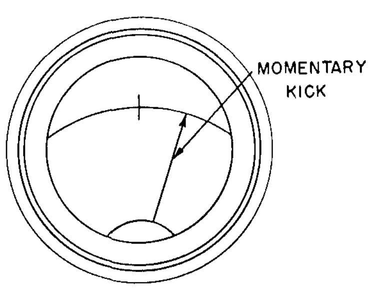


FIGURE 33. Right-left meter deviation indication.

With this, the meter can be kept short-circuited except during the time that the desired echo is being received.

Right-Left Indicator with Sweep. The right-left indicator (Figure 34) finally used in the X-3 BDI is the most useful of all the indicators which were tested extensively. This indicator resolves a large number of deflections close together better than the other indicators. It also gives the simplest and most direct deviation indication for the sound operator to follow.

DOPPLERIZED BDI

Operational reports on the tactical use of BDI made it appear worthwhile to investigate the possibility of developing a unit that would show greater discrimination between the target echo deflection and the deflections caused by wake echoes and reverberation. Since basic techniques, especially the *own-doppler nullifier* [ODN] (see Section 4.3) and RCG (see Section 2.5) were already available for achieving these ends for audible sound, it was natural that attempts should be made to adapt the same developments to the BDI. An early attempt to apply RCG to the BDI showed that it could be done at the expense of an additional amplifier stage and an additional rectifier. This, however, was considered at the time to be too high a price for the advantage resulting from replacing TVG by RCG.

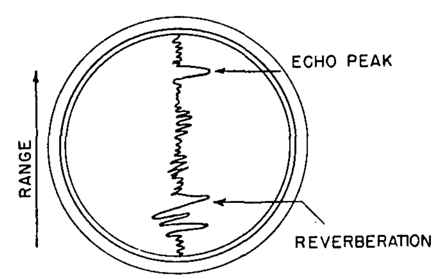


FIGURE 34. X-3 bearing deviation indication (target to right).

The next approach to the problem dealt with the enhancement of dopplerized echoes. All signals were allowed to come through and to be impressed on the cathode-ray deviation indicator. When, however, some component of

the signal-complex showed doppler, it activated a frequency-discriminating circuit which increased the gain of the system during the time the dopplerized signal was coming through. This served to emphasize the part of the signal —i.e., the echo from the moving submarine— while still giving target deflections of ordinary size on undopplerized signals.

Target Range by BDI Triangulation

Some thought was given at one time to the possibility of installing a BDI at each end of a ship and obtaining target range by triangulation without echo ranging. No extensive experiments along this line were conducted. What work was done, however, indicated that although the BDI could be so used, such an application would place severe demands on the maintenance of alignment of the BDI circuits.

BDI and Scanning Sonar

During the development of scanning sonar receivers it was suggested that their bearing resolution and accuracy might be improved by using simultaneous lobe comparison techniques. To test this proposal a number of experiments were performed in which two beams separated by a small angle were rotated, the signal received on one beam being balanced against that received on the other. Thus the voltage pulse resulting from the arrival of an echo would be first positive and then negative and the spot on the CRO screen brightened at the instant of crossover between the two pulses. Although the scheme showed some promise in the light of the experiments, it was discarded at that time because of the comparatively poor cathode-ray scope indication and the complexity of the equipment. The study of the application of BDI to scanning systems was, however, revived later.[c]

BDI and Depth Determination

It was natural also for BDI techniques to be extended to depth determination. Two BDI units were attached to a projector which was split electrically into four quadrants, the connections from each being brought out separately.[17] By properly combining the connections from the quadrants it is possible to have the projector split into right and left halves and top and bottom halves. One BDI unit is used with the right-left arrangement to indicate the usual azimuth bearing deviation. A second BDI connected to the top and bottom halves gives a depth angle deviation when the projector is trained in depth, i.e., about a horizontal axis. The installation was essentially routine except for the problem of isolating the inputs of the two BDI's since they have certain quadrants of the projector in common. A new sonar transmitter was designed for use in this application, called the dual frequency driver.[18] It delivers energy simultaneously at two ultrasonic frequencies to the quadrant-split projector, thus permitting sound beams of different widths to be used for determining the bearing and depression angles of a submerged target. The respective frequencies of the two channels of the driver are separately adjustable, one over a frequency band extending from 18 to 35 kc, the other from 35 to 70 kc.

Some work was also done in the design and construction of a unit modeled after a British depth-measuring projector called the "Sword," but split for BDI operation.

BDI and Integrated Sonar

The purpose of the integrated sonar system development was to incorporate into a single coherently designed equipment the many features which had been added as attachments to the original QC gear and to use scanning sonar techniques to improve searching efficiency. Among other components which were amenable to redesign on such a basis was the BDI. The previous models had by this time been tested under a variety of conditions, and clearer ideas could be formulated concerning their relative importance in meeting the various manufacturing and operational needs. As a part of this integrated system, therefore, design work was begun on another BDI.

Considerations of stability, economy of com-

[c] A detailed explanation will be found in Division 6, Volume 16 on *Scanning Sonar Systems*.

ponents, and uniformity in the integrated system made it appear desirable to employ the sum-and-difference method to give the desired bearing deviation sensitivity.

In this type of BDI, which is described in detail in Section 5.7, the sum of the signal voltages from the halves of the split projector is fed into one channel, and the difference into the other. The two signals, representing the sum and difference, are combined at the output of the amplifiers to give a right-left indication. Although at first this appears to differ from the BDI types which employ lag lines, it is, nevertheless, true simultaneous lobe comparison since mathematical analysis shows that shifted lobes do appear in the output.

Testing Equipment

In order to facilitate testing of BDI equipment, various items were developed. These include the split projector test unit and the phase-sensitivity test unit, both of which are described in detail in reference 23.

Split Projectors

A detailed analysis of split projectors is given in the report entitled "Bearing Deviation Indicator."[1]

5.9 RECOMMENDATIONS FOR FUTURE WORK

General Recommendations

A desirable goal for future work in BDI should be simplifications in circuits and in operation of the equipment. Application of RCG techniques, which relieve the BDI operator of TVG and gain monitoring, is one example. Of even greater basic importance is the work on simplifying the deviation indicator trace by application of doppler-sensitizing circuits (see Section 5.8). The advantages of utilizing the frequency difference between the echo and the extraneous sound are best appreciated by one who has attempted to maintain contact on a weak echo some decibels below the reverberation intensity. This can be done even when the echo is so weak as to give not the slightest distinguishable echo deflection on the BDI trace, provided that it has doppler. Any system which works only on the amplitude of sound and ignores frequency differences is neglecting possible utilization of an extremely useful parameter. BDI in its present forms is ignoring this.

Successful application of frequency-discriminating techniques will free the sonar operator from the complications introduced by wakes and reverberation and thereby provide a simple solution of the present comparatively complex problem of audible-visual correlation.

Certain measures are possible for standardizing the BDI performance. Lag lines which afford a constant phase shift and a constant impedance independent of the operating frequency would help effect such standardization. A correlative aid would be testing of projectors by means of beam patterns and phase tests before they are installed and rejecting those which fail to meet certain established standards.

Conveniently located and simply operated test equipment built into the instrument would make easier the job of maintaining the BDI at peak efficiency. The final aim in such equipment should be to make it possible for the sonar operator to test operation and carry out adjustments by the simple expedient of observing the action of a meter. The deviation indicator tube itself might serve as such a meter. If this is not possible, external test gear should be developed to enable frequent checking and adjustment in the field.

Specific Recommendations for BDI Components

Projector Testing. The split projector used with BDI should conform to certain minimum requirements to insure that the BDI performance will be satisfactory. The economy of effort in installing only good projectors is obvious, in that changing a projector is a laborious task and usually requires dry-docking facilities.

Recommended methods for doing this are described in the reports on projector test gear[19] and split projector test units.[20] Beam patterns

are described in the report on field studies of sonar domes.[21]

BDI Brightening. The conventional echo brightening circuit increases the brilliance of the cathode-ray trace whenever the absolute level of the received signal is a given value above the TVG curve at any given instant. This requires careful TVG matching for local conditions as well as careful gain control adjustment. An inevitable result is the occasional brightening of the trace for a considerable period of time because of bottom reverberation or other factors causing the amplitude threshold to be exceeded.

Figure 35 shows a proposed circuit which was designed to give a dynamic form of bright-

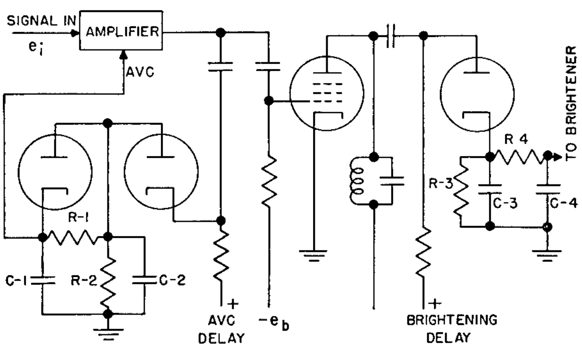


FIGURE 35. Proposed circuit for dynamic brightening.

ening with a sharp threshold without any manual controls. The AVC amplifier is designed to give a steady-state output, e_o. The bias e_b on the class C stage is arranged to keep the grid of that stage below cutoff even on the positive peaks of the AVC amplifier output. A sudden increase of input voltage, e_i, then produces a corresponding increase in AVC amplifier output, because of the AVC time constants. Therefore, the class C stage delivers an output signal as soon as the peaks of e_o exceed the cutoff voltage on the control grid of the class C stage. If the brightening rectifier includes some delay voltage, an extremely sharp on-off brightening characteristic should be obtained.

By properly adjusting the absolute and relative values of AVC amplifier output and cutoff bias, various amplitude thresholds may be obtained.

Provisions must be made to prevent the AVC system from being blanked out by wake echoes or similar extraneous disturbances immediately preceding reception of a target echo. To this end, a discharge diode section is installed across R-1 in order to discharge C-1 rapidly. If R-1 is ten times the value of R-2, and if C-2 is kept very small, the attack and release times of the AVC system will be approximately equal.[22]

To avoid appreciable brightening on noise spikes, the R-4, C-4 time constant should be relatively long, and R-4 should have about ten times the resistance of R-3. The capacitances C-2 and C-3 should be as small as possible compatible with peak carrier rectification.

Automatic Oscillator Tracking. A scheme such as is shown in Figure 36 might be used to assure that the beat-frequency oscillators in Model X-3 always track. This proposal consists in feeding one channel directly from a variable oscillator and feeding the other from a mixer which gives the sum of the variable oscillator frequency plus the difference frequency for the two channels. In this manner, the difference frequency could always be maintained, i.e., the oscillators would always track, provided the fixed oscillator was correctly set initially, and maintained its frequency under operating conditions.

The scheme could be varied from that shown by having two fixed oscillators, one for each of the channels. A variable-frequency oscillator could be heterodyned with each of these to give a frequency proper for each channel. If the fixed oscillators were properly adjusted, the requisite frequency difference between the two channels could be automatically maintained.

Push-Pull Deflection Amplifier. In the single-ended deflection amplifier used in the X-3 BDI, the deflection coil is placed in the cathode circuit. Current is fed from the negative power supply through the coil in opposition to the cathode current. This results in a reduction in sensitivity of the amplifier because of degeneration.

The circuit of Figure 37 is a push-pull deflection amplifier excited by a single-ended phase-sensitive detector in a kind of d-c phase

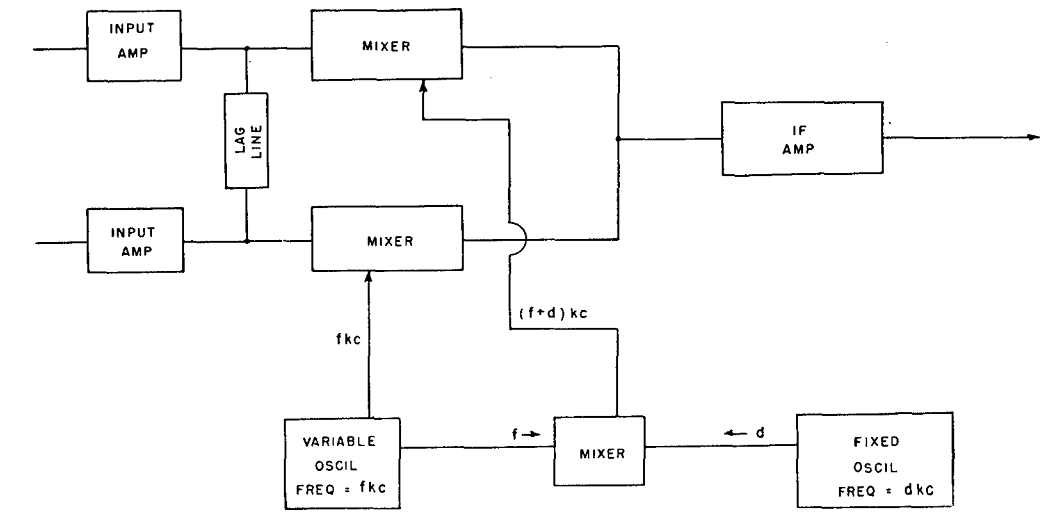


FIGURE 36. Scheme for automatic oscillator tracking.

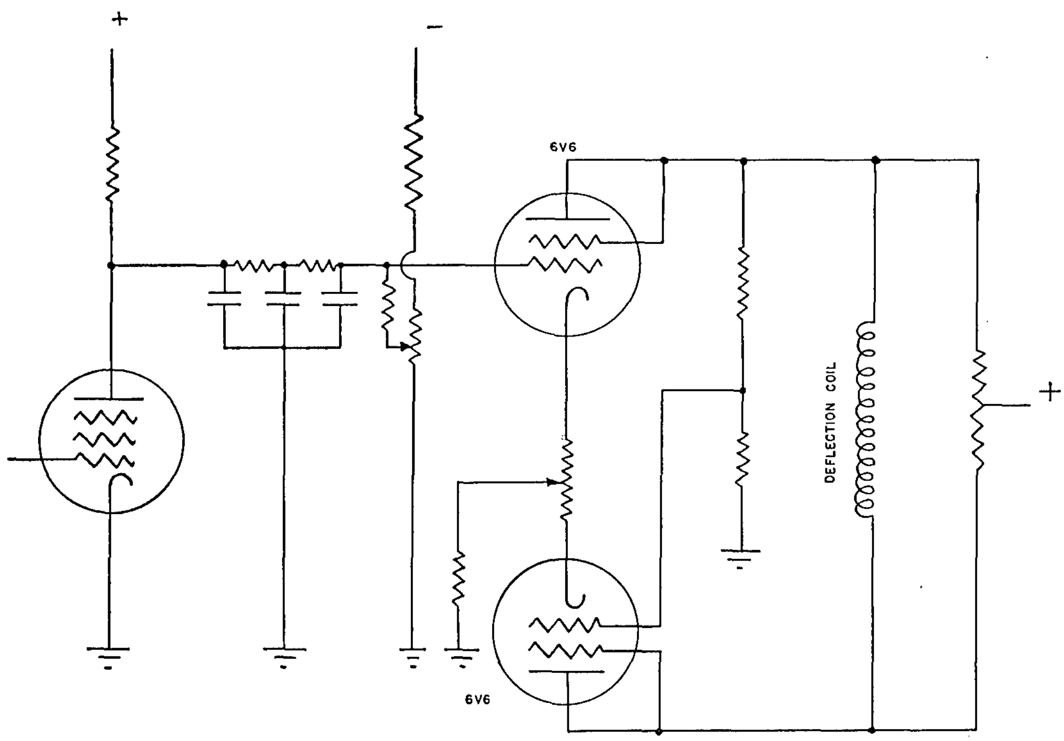


FIGURE 37. Push-pull deflection amplifier.

inverter circuit. It should have less drift than a single-ended deflection amplifier yet it does not require push-pull phase-sensitive detectors. The increase in gain realized by putting the coil in the plate circuit makes it possible to increase the stability by using degeneration in the cathode of the phase-sensitive detector.

By proper construction of the coil it might be found advantageous to feed the 6V6 plates (see Figure 37) through the deflection coils.

The use of push-pull deflection circuits and push-pull or balanced arrangements in those portions of the BDI employing d-c amplification worked out very well in the polar presentation

BDI.[1] These methods should be considered wherever high stability and accuracy are desired.

Separate Amplifiers with Pilot Signal Control. A persistent difficulty in BDI circuit design stems from the necessity of providing for equal amplification of the signals from the right- and left-steered channels. Much of the development work described above has been devoted to various solutions of this problem. One method of attack which has been used successfully in a similar design problem involves the use of a pilot signal having a frequency different from other frequencies involved in the BDI circuit. This pilot signal is generated by a separate local oscillator and applied to the input circuits of the right and left channel amplifiers which may now be completely separate. A filter in the output of each channel amplifier selects the pilot tone for rectification and application as grid bias for AVC in the channel amplifiers. Since the same pilot signal is applied at each input circuit, AVC at the pilot tone frequency insures that the gains of the two channels remain identical within limits determined by the similarity of the AVC characteristics. If TVG or RCG is to be applied to the BDI system, it may be introduced through a single-stage variable-gain amplifier supplying the common pilot tone to the two channel amplifiers.

This system has been tested experimentally only in connection with BDI systems intended for use on broad-band noise, but there appears to be no reason why it might not also be utilized advantageously in BDI systems for echo ranging.

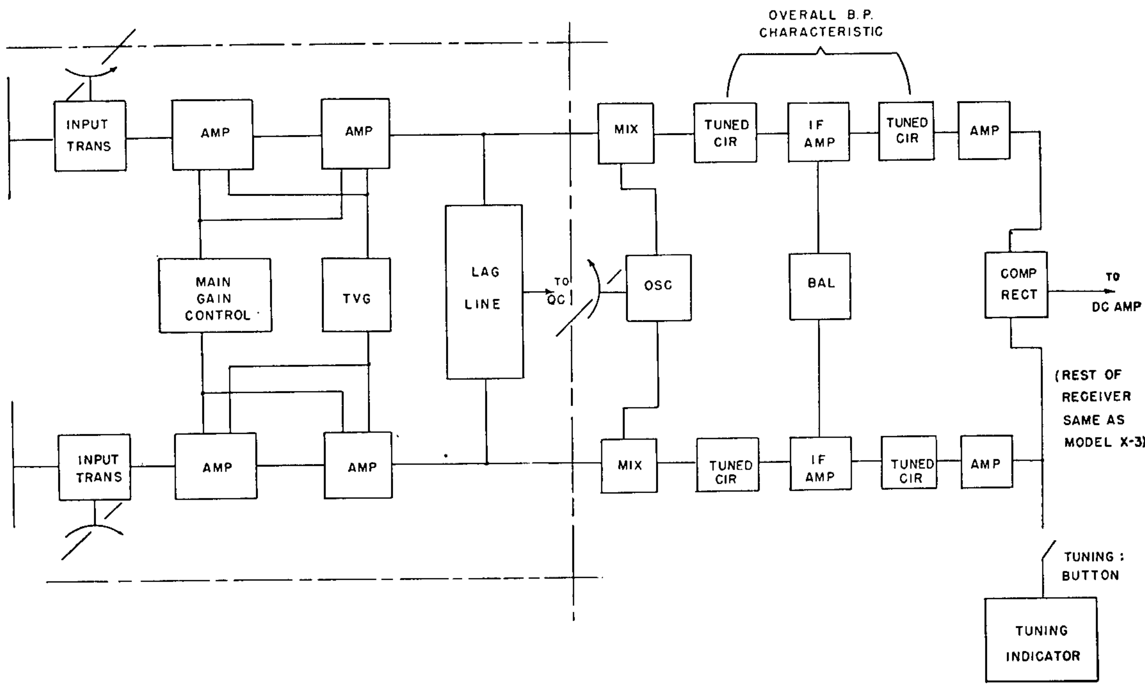


FIGURE 38. Block diagram of alternate BDI circuit No. 1.

Alternate BDI Circuits. Figure 38 is the block diagram of an alternate BDI circuit, with some improved features.

The most noteworthy changes are the application of gain control, both manual and TVG, ahead of the lag line, the use of the same intermediate frequency in both channels, the ganging of oscillator and input tuning, and the use of a cathode-ray tuning indicator.

The purpose of applying gain control ahead of the lag line is to permit both signals to be controlled simultaneously, without resorting to a common channel amplifier with the at-

tendant difficulties of matching band-pass filters for different channel frequencies. Because change, within reason, in relative amplitude of the signals ahead of the lag line, does not affect the reliability of the BDI indication, the gain may readily be controlled at this point provided no relative phase shift is introduced. It is believed possible to have two medium gain untuned or semi-tuned stages of amplification ahead of the lag line without producing detrimental phase shift.

A single oscillator is used for two reasons: first, to eliminate tracking difficulties; and second, to permit balanced amplification and filtering at the same frequency in both channels.

Some simplification of the band-pass filters should result from the use of the same frequency for both channels. Three-winding television-type band-pass filters might be tried or the circuit consisting of two tuned circuits of equal Q used as one interstage transformer, and a single tuned stage with a Q only half as large used for the next interstage coupling device as shown diagrammatically in Figure 39. Such a circuit gives a flat top effect regard-

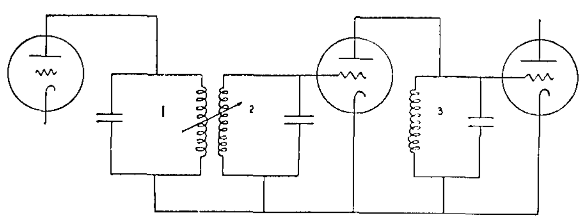


FIGURE 39. Flat top interstage coupling system.

less of the amount of coupling used. It would seem that it should be easy to adjust because of this feature. By use of high-Q circuits (1 and 2) the overall band-pass characteristics should be at least as steep-sided as the overall characteristic for the X-3 BDI.

By using a cathode-ray indicator while tuning the BDI receiver assurance will be given that operation will always be in the middle of the pass band so that the flat top can be made only wide enough to allow for maximum anticipated change of frequency because of doppler. The indicator should be of the self-rectifying type having a high-Q circuit across the input and tuned to the intermediate frequency as shown in Figure 40.

If sufficient selectivity can be obtained in the band-pass filters, it may not be necessary to tune the input circuit. If any tuning is neces-

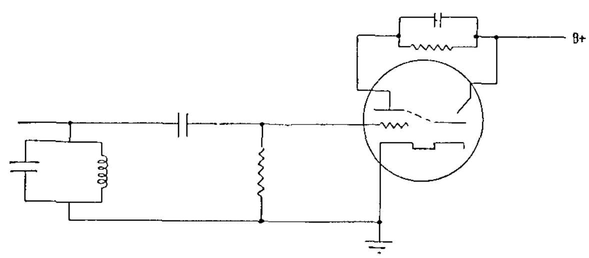


FIGURE 40. Details of self-rectifying indicator.

sary, it should be of low-Q nature in order not to be critical from a phase-shift standpoint and it should be ganged to the oscillator tuning, thus requiring a three-gang condenser. To change frequency, it would merely be necessary to depress the tuning button to connect in the tuning indicator, and rotate the tuning dial for minimum shadow while the sonar driver key is depressed.

The i-f amplifiers would have to have a large dynamic range; 6AG7 tubes would probably be satisfactory. The balance control would be in the screen circuits of these i-f amplifier tubes.

Another alternate BDI circuit combining the advantages of the X-4 and the sum-and-difference BDI is shown in the block diagram of Figure 41. The sum and difference of the outputs from the halves of the split projector are obtained by the connections shown. Modulator A has its large signal supplied transversely by the oscillator. Its small signal, supplied longitudinally, is the difference signal. The output of this modulator consists of the two side bands with the carrier suppressed. After an appropriate phase shift (to bring the resultant of the side bands into phase with the sum signal) these signals are added and amplified in the RCG-controlled amplifier. Combination of this modulated carrier with the oscillator voltage in the phase-sensitive rectifier gives a direct current proportional to the signal amplitude and the deviation with the proper sense.

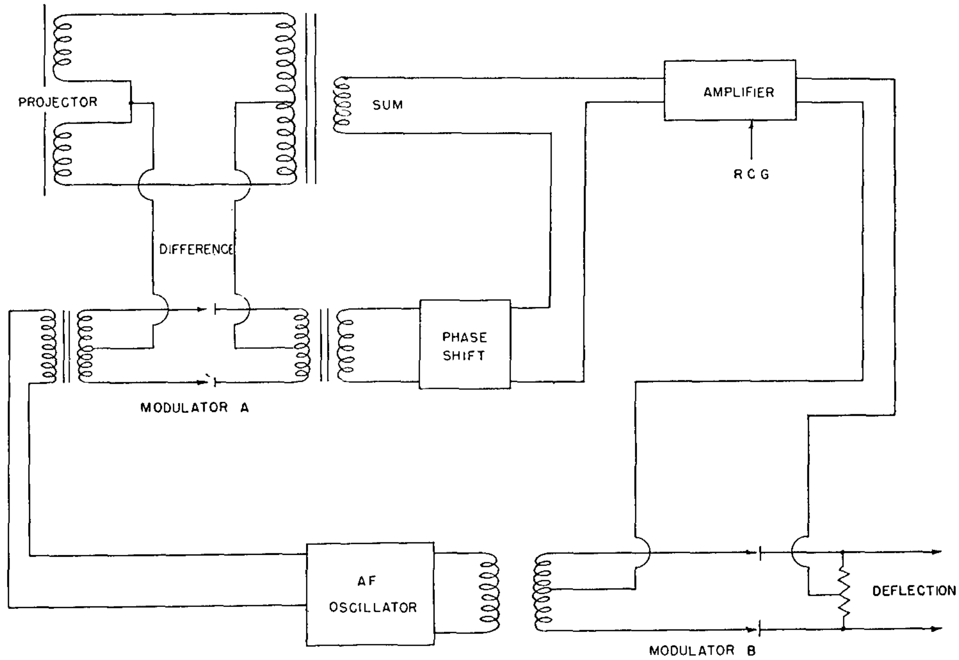


FIGURE 41. Block diagram of alternate BDI circuit No. 2.

The sinusoidal modulation allows a narrower amplifier bandwidth and the combination of sum-and-difference signals before amplification allows a definite relationship to be set up between their various gains. The effective lag line can be held constant, therefore, at its optimum value for the type of deviation curve desired.

Double Pinging. Another approach might be to obtain a sequence of signals significantly different from reverberation by double pinging. (This method is sometimes used by the operator to verify contacts.) Figure 42 suggests a possible form of visual presentation of double-ping information. The circuit is intended to produce cathode-ray tube brightening on the second echo when the two echoes are separated by a definite time interval. Upon reception of the first echo, the negative rectifier cuts off the series triode between the positive rectifier and the cathode-ray tube, thereby preventing transfer of brightening to point *C*. When the first echo dies away, the negative control grid voltage immediately drops, and brightening voltage is transferred to point *C*. Since, however, the grid of the shunt triode is at ground potential, none of this voltage appears at the output of the system. Upon reception of the second echo, the grid of the shunt triode is driven negative, and any voltage then present at *C* is applied to the

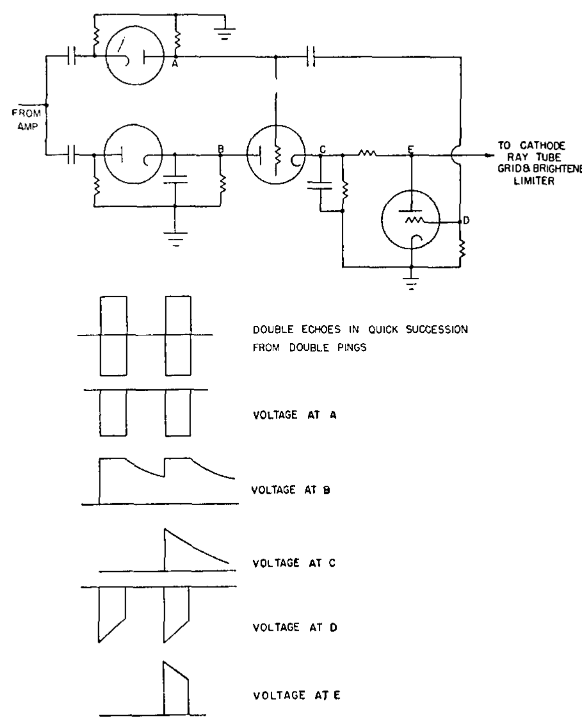


FIGURE 42. Coded pulse brightening system for BDI.

cathode-ray tube grid. If a second echo does not arrive, the voltage at C reaches ground potential and that circuit is cleared for another cycle of operation.

This brightening system, which is dependent on changes of level, might be used in connection with the conventional X-3 brightening system to increase the dynamic range of brightening on the cathode-ray tube.

Proportional Deflection BDI. Frequent reference is made to the tactical advantages which might accrue if the deflections of the BDI were accurately proportional to the deviation angle of the echo target. These advantages would appear to be so compelling as to demand an explanation of why proportionality has not been provided in HUSL BDI systems.

Most BDI deflection circuits which provide proportional indication incorporate either AVC or limiters to remove amplitude variations for purposes of making the indication responsive to phase alone. This automatically produces proportionality, since the relative phase at the two projector segments is a function only of the angle of arrival of the incident signal. It necessarily follows that a low level signal such as a small burst of reverberation or noise originating, say, to the right of the projector will produce the same deflection as a strong target echo similarly located. Since reverberation and noise each fluctuate in both amplitude and direction of arrival, it becomes obviously necessary to provide some form of amplitude threshold level which must be exceeded before a bearing deviation is indicated to the operator. This requirement in turn denies to the operator the coordination of audible and visible responses for echo signals which are very close to the noise or reverberation level.

Another method of presenting the available information in a proportional BDI system involves the use of signal intensity to provide Z-axis modulation or spot intensity control for a CRO display in which angular deviation is shown by right or left deflection of the echo spot, all imposed on a vertical range sweep. This method can be used in a display such as the sector scan system developed by the Naval Research Laboratory. It is well known, however, that the eye is very much less responsive to changes in intensity than it is to physical displacements. Thus, one obtains proportionality of bearing deviation indication in this case at the expense of some of the visual cues to echo recognition afforded by the conventional right-left indication of the HUSL BDI systems.

The undeniable operating convenience of a proportional indicator and the incidental advantages which might accrue in the easier design of automatic target training systems would justify a recommendation that further development work be devoted to this design and presentation problem.

5.10 EVALUATION OF PERFORMANCE

As would be expected with any new equipment, the first few months of its operation raised certain questions which could be answered only in the light of a considerable amount of experimental evidence. Among these, in the case of BDI, were the following.

1. To what extent is the BDI susceptible to being misled by the submarine's wake?

2. What can be learned as to the quality and quantity of the information which the BDI furnishes to the conning officer and the sound officer?

3. What can be learned as to the ability of Service personnel to operate the BDI effectively?

Experiments were undertaken to answer these questions. The data gathered were of the following two sorts.

1. Observations made during a series of 150 BDI runs on a submarine employing full evasive tactics.

2. About 2,200 each of BDI and cut-on observations on a submarine running at periscope depth.

Two groups of Navy personnel constituted the BDI operators during these tests. One consisted of sound instructors with from three to six months' BDI experience. The other group was made up of recent graduates of the fleet sound schools who had no previous experience in BDI operation. By conducting the tests in this manner, operation of the equipment by approximately typical field personnel was assured.

5.10.1 General Conclusions

COMPARISON OF BDI WITH CUT-ONS

The principal conclusions drawn from these experiments may be summarized as follows.

1. BDI average bearing errors are less than computed center bearing errors.
2. The shaded band (dispersion of bearings) for the BDI data is narrower than that for the computed center bearing, indicating that the BDI gives the more reliable information.
3. The BDI bearing is a more accurate and reliable reference point than either the leading edge or the trailing edge.
4. During search, BDI is of aid as a visual check on contact.
5. BDI is extremely useful in helping hold the target during the initial rapid turn to head for the contact.
6. Because of its smaller dispersion and the fact that it supplies bearing information more rapidly, the BDI increases appreciably the ability of the sound operator to recognize bearing drift. Increased rapidity of flow of information and increased bearing accuracy are both of considerable value during the fast-moving attack on a bow target.
7. With BDI operation, a more easily distinguished doppler shift is obtained. This is caused by the fact that since proper BDI operation calls for the sound beam to be on the target at all times, an echo is obtained on almost every ping, so that less "pitch memory" is required to compare successive echoes for doppler shift.
8. With BDI operation, an almost unbroken sound range recorder trace is obtained. Right and left edges of the trace line up fairly evenly regardless of target aspect. This facilitates determination of range rate and firing time, particularly for ahead-thrown weapons.

DEPENDENCE OF BDI ON OPERATOR SKILL

As mentioned earlier, two general groups of operators were used. Consequently, a comparison of the performance of BDI in relatively skilled and unskilled hands was possible.

The sound instructors, with from three to six months' experience with BDI obtained 70 per cent of all their BDI bearings within ±2 degrees of the periscope. Fleet sound school graduates, after only one lecture and one or two practice runs on BDI, also obtained 70 per cent of all their BDI bearings within a ±2-degree band. Scoring the two groups on cut-ons showed the superiority of the more experienced men, who obtained 48 per cent of their computed center bearings within a ±2-degree band, as compared to 34 per cent for the recent sound school graduates. The percentages are based on 2,200 BDI observations (1,350 by instructors, 850 by sound school graduates) and 2,150 cut-on observations (650 by instructors, 1,500 by graduates). These results indicate that BDI operation is relatively easily learned.

BDI DEFLECTION AND ECHO STRENGTH

The question is sometimes raised as to whether or not the BDI will give deflections for all audible echoes. The answer is that it will not. Sometimes a very weak echo, chiefly distinguishable by doppler shift, can be heard when no observable echo appears on the BDI screen. This is particularly true when wake or reverberation is affecting the BDI trace. On the other hand, sometimes echoes which might conceivably be unnoticed by the ear can be seen on the screen. This is most frequently true for echoes with little or no doppler. It is not of frequent occurrence.

SOUND RECORDER TRACES WITH BDI OPERATION

The sound range recorder trace undergoes some changes when BDI center bearings are being used. All these changes stem from the fact that the sound beam is, on the average, much closer to the target center than it is in cut-on operation. Therefore, the "wake loops" which appear as characteristics of bow or quarter targets in cut-on operation, are minimized in good BDI operation. The echo trace shows some individuality for target angles about 20 degrees either side of direct bow or direct stern. The remaining wide angles either side of beam are fairly indistinguishable as regards the chemical recorder trace.

The BDI chemical recorder trace, however, is highly intelligible, especially when used in con-

junction with doppler. The even appearance of the echo trace facilitates accurate range rate readings as well as firing time determinations.

5.10.2 Summary of BDI Doctrine Proposals

There have been four major sources of proposals for BDI doctrine. The following is a brief comparison of the chief points in the proposals:

1. All are in agreement that the BDI trace must be interpreted audibly plus visually. Two specifically include drawings to aid the operator in distinguishing between wake and hull indications in the various target aspects. These sets of drawings are in close accord.

2. The question of the beam submarine (undopplerized echo) is treated in the four proposals as follows.

   a. Two recommend that BDI not be used on a beam submarine.

   b. One recommends that BDI be used, but that bow cut-ons be interspersed among the center bearings.

   c. One recommends that BDI be used and that the operator train forward every third or fourth ping to get a leading deflection.

3. All proposals caution that the operator should lead the target center frequently, and that attempting to stay always exactly on a center bearing is dangerous.

4. One proposes that after three or four BDI center bearings are obtained, the operator take cut-ons and then return for three or four more BDI bearings. Such procedure has the advantage of preserving certain features of the sound range recorder trace characteristic of cut-on operation, but it would probably rob BDI of many of its most valuable attributes.

As is evident from these comparisons, there is good agreement on many important points. With the exception of the treatment of the beam target, three of the four proposals are in close agreement.

Chapter 6

ECHO-RANGING RECEIVING EQUIPMENT

An Improved Echo-Ranging Receiving Equipment

The improved echo-ranging receiving equipment was designed as a replacement unit for existing receiving racks, to provide greater operator comfort and efficiency and improved accessibility for maintenance. The unit is a console-type construction with provision for seating the sound operator comfortably. The single console includes MTB, BDI, TVG, a chemical range recorder, and a CRO for presentation of the echo pattern. Six preproduction consoles were built by CUDWR-NLL and were used as guides for production models. The production consoles were manufactured by the Submarine Signal Company and the Radio Corporation of America Manufacturing Company and respectively designated by the Navy as the QGA and QGB.

6.1 INTRODUCTION

The arrangement of components in the old style echo-ranging rack, with the range and bearing indicators widely separated from the most important operating controls, made it difficult for the sound operator to observe and control the equipment. This difficulty was enhanced by several undesirable characteristics of the gear: (1) the true bearing of the projector was a function both of the adjustment of the training control and of the ship's heading, (2) no direct means was available to indicate the direction of training adjustment necessary to stay on a target, and (3) the level of initial reverberation fatigued the ears of the sound operator.

A development program was undertaken for the purpose of incorporating improved circuits in a more conveniently arranged receiving rack. These included *maintenance of true bearing* [MTB] (see Section 3.7), *bearing deviation indication* [BDI] (see Section 5.2), and *time variation of gain* [TVG] (see Section 2.2), all of which had been initiated earlier as separate projects. In addition, the modified rack included a chemical recorder for indicating range, oscilloscopic presentation of the echo pattern, and several other new operating features.

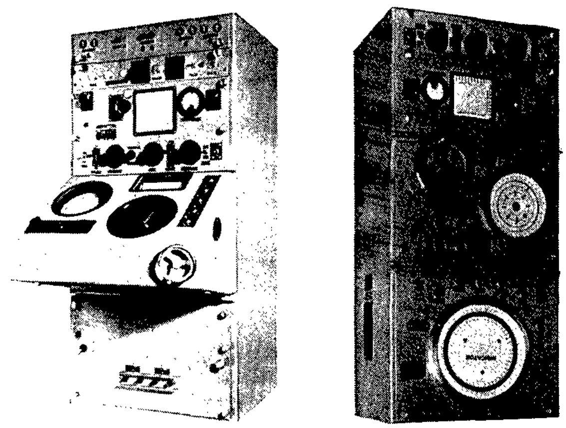


FIGURE 1. Sonar receiving equipment; *left*, the Mark II improved echo-ranging receiving rack; *right*, the existing sonar "stack-type" rack.

The physical arrangement of the modified equipment provided a console type of construction, permitting a concentration of the most important indicators and operating controls in a convenient location for a seated operator, as well as greater accessibility for maintenance and repair. The new features and arrangement combined to increase markedly the range and bearing information obtainable per unit of time.

By the time this program was completed the need for new gear was so great as to require the manufacture of complete echo-ranging systems rather than replacement receiver racks. Consequently, the modified rack, Mark II, was used for extensive tests of the new features and physical arrangement and as a guide in the development by manufacturers of equipment for installation on new ships.

6.2 DESIGN CONSIDERATIONS

Because echo-ranging gear must be manned continuously for long periods of time and dur-

ing all conditions of sea, maximum provision was made for the comfort and efficiency of the operator. Range and bearing indicators and most important operating controls were located where they could most easily be observed and adjusted.

With relative-bearing projector training, the necessity of compensating for changes in the heading of the searching vessel increases the time required to obtain range and bearing readings. These bearing compensations also increase the difficulty of retaining a target once it has been located. Therefore a means was provided for maintaining a constant true bearing orientation of the projector except for changes made by the operator.

A method of indicating right or left deviations between the bearing of the projector and that of the target was incorporated so that, upon obtaining a contact, the operator could immediately correct the projector bearing without recourse to constant cutting on and off the target.

The rate of opening or closing of target range, obtained by comparison of several successive range indications, is information of primary importance to the attack problem. For this reason, and in order to aid the operator in estimating the location of partially obscured echoes, a means was provided for automatically recording range.

Since signals due to reverberation generally differ in pattern from well-defined target echoes, visual presentation of the entire reverberation pattern was provided as an aid to the detection of weak echoes from real targets.

Certain information concerning the character of the target is best obtained from an audible signal even when the range and bearing information is adequately presented by visual indicators. Therefore, a method was devised for suppressing initial reverberation, by means of an automatic gain control circuit, to reduce the aural fatigue of the operator.

To avoid operator eyestrain, attention was given to balancing the lighting of the indicators.

An initial objective in the development of the modified rack was the design of a receiver console which could be substituted for existing gear without extensive alterations to the other components of the echo-ranging equipment or to the ship. With this objective in mind, the modified equipment was designed to fit existing rack frames, to make maximum use of components already in production, and to connect to cables from other components of the existing equipment.

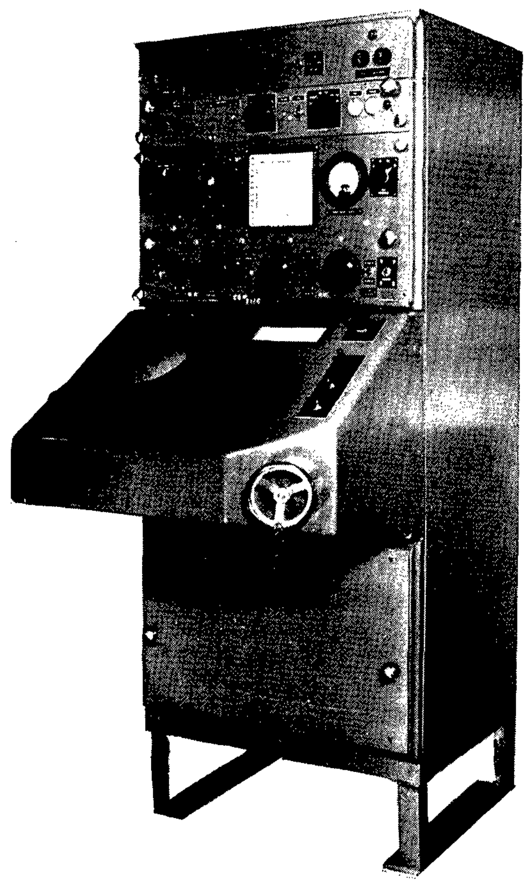


FIGURE 2. Mark I improved echo-ranging receiving rack.

6.3 THE MARK I RACK

The Mark I model, is shown in Figure 2. This unit, with the most important indicators and operating controls located on a console, incorporated true bearing training of the projector (MTB), a means of indicating the right or left deviations of projector bearing (BDI), and a circuit for time variation of the receiver gain (TVG). In addition, the Mark I unit employed a chemical recorder for indicating range, balanced fluorescent lighting of the indicators,

and presented the BDI indications and the echo pattern on a single oscilloscope.

In the development of this first model, a number of schemes were investigated and discarded. A flashing neon-lamp type of range indicator with a circular range scale was abandoned in favor of the chemical range recorder. The use of twin amplifiers of new design or of two standard echo-ranging receivers was proposed as a means of providing BDI amplification. However, because these lacked adequate phase and amplitude stability, a *simultaneous lobe comparison* [SLC] amplifier circuit (see Section 5.2) was selected. Although two 5-in. *cathode-ray oscilloscope* [CRO] tubes were used initially to present the BDI indications and the echo pattern trace, the development of a means of superimposing the BDI trace on the echo pattern oscilloscope eliminated the necessity for two tubes.

After the performance of the Mark I had been satisfactorily demonstrated in sea tests, this model was used as a guide in the design and construction of four additional units, all designated as Mark II, to be used as preproduction models and for further tests to evaluate more fully the new features and arrangement.

6.4 THE MARK II RACK

Although research had resulted in several new and promising developments since construction of the Mark I, to speed up the delivery of production units no extensive rearrangements were incorporated in the Mark II equipment. A number of modifications were made, however, in order to incorporate improvements which experience and testing of the earlier unit had indicated to be necessary for optimum performance.

Improved BDI circuits necessitated redesign of the physical layout of the BDI amplifier. A new MTB circuit was included which eliminated the differential gearing in the follow-up system of the Mark I rack. A further change in the new model was the addition of a second pen on the chemical range recorder to record the right-left indications. This second pen, in addition to providing a permanent record of the right-left deviations, made the range recorder a stand-by for the CRO equipment.

During the later stages of construction of the Mark II equipment the addition of *automatic volume control* [AVC] was considered and a suitable system was developed.[1] AVC was added to two Mark II units which had been installed on Navy sound school vessels for tests, but the small improvement over TVG did not warrant the increased complication of the equipment.

General Arrangement

The Mark II modified receiving rack is shown in Figure 1. The power-supply circuits are located in the bottom panel below the indicator and control console and the standard heterodyne receiver is located directly above the console, thereby making the most important operating controls conveniently accessible to the operator. Above the receiver, the BDI circuits fill the remaining space to the top of the rack, leaving panel space at the top for the switches controlling the power supply to the driver circuits and hoisting motors.

Particular consideration was given to arranging the rack in such a manner as to facilitate accessibility for inspection and maintenance of all the components. The console, hinged at its lower edge, swings down to give access to the CRO and range recorder which may each be dropped forward to expose the wiring. The power supply, receiver, and BDI chassis each pulls out on rails to expose the top of the unit, and pivots as illustrated in Figure 3 to expose the wiring on the under side. The power control panel is hinged at the top edge and swings up to give access to its back side and to permit the BDI chassis to be pulled out.

Maintenance of True Bearing [MTB]

The MTB arrangement of the modified echo-ranging equipment holds the projector axis in a constant true bearing orientation unless changes are made by the sound operator. The mechanism used to accomplish this employs signals from the gyro compass to permit automatic control of the projector bearing by a rearranged servo system (see Section 3.8).

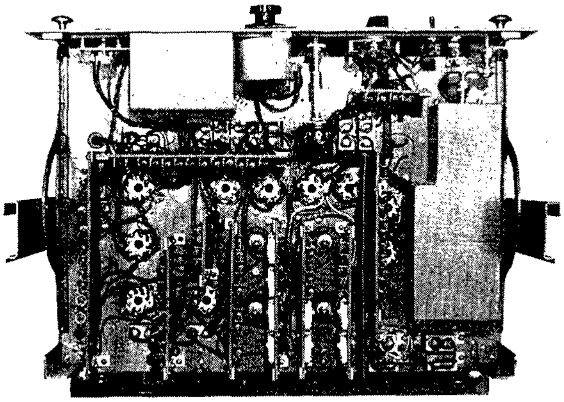


FIGURE 3. Bottom view of BDI amplifier chassis, showing accessibility arrangements.

In the type of MTB system first incorporated in the Mark II rack, the bearing dial was arranged with the true bearing scale on the fixed outer ring and the relative bearing scale on the moving inner section, a reversal of the original significance of these dial elements. About the time the first Mark II units were put into operation, a directive was issued which required the use of an indicator having dials with the conventional arrangement, i.e., with true bearing indicated by a moving inner scale and relative bearing shown on the fixed outer ring. This necessitated a redesign of the MTB unit and the new system was added to the Mark II units on sound school vessels as a field modification.

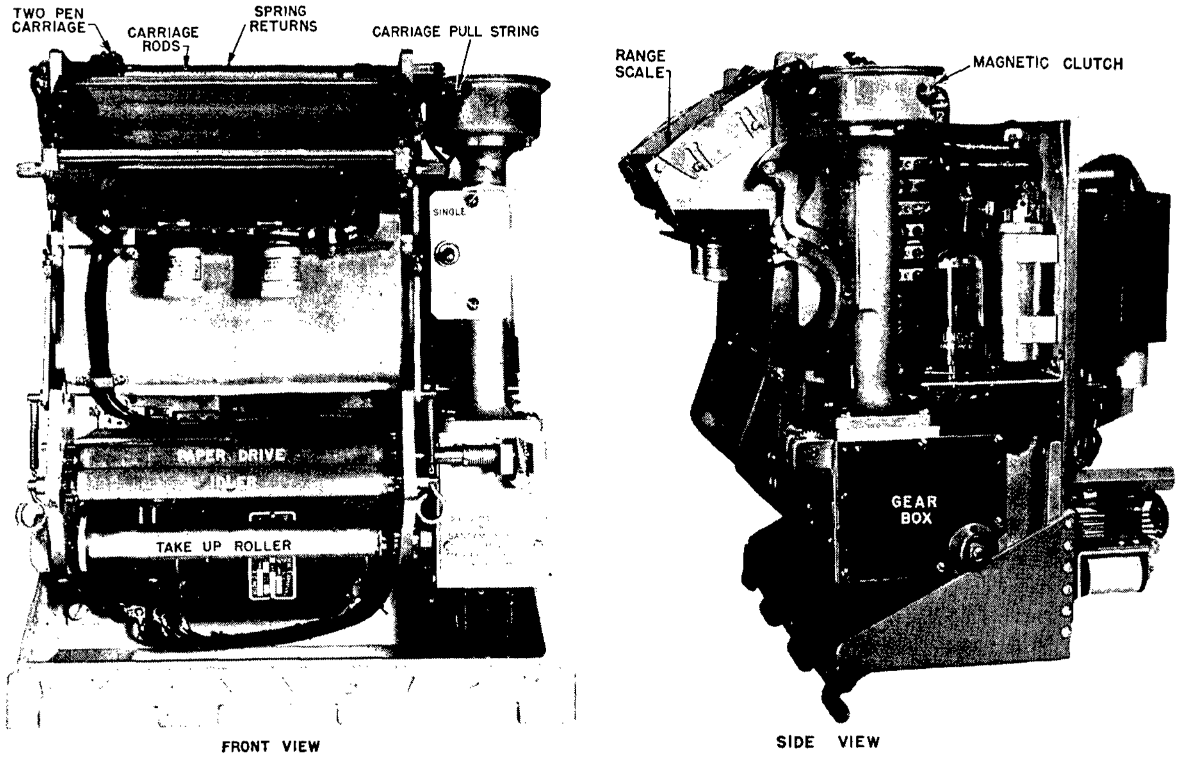


FIGURE 4. Two-pen Sangamo chemical range recorder.

BEARING DEVIATION INDICATION

Indication of right or left deviation of the projector axis from the center target bearing is accomplished in the Mark II rack by simultaneous lobe comparison (see Section 5.2). In essence, the SLC amplifier circuit provides a means of obtaining bearing deviation indications from a single projector electrically split into two halves. The signal from each half is fed into its own amplifier, oscillator, and modulator, and the two circuits are interconnected by a phase-delay network, so that the phase difference between the voltages received from the right and left projector halves is converted

to an amplitude difference in the signals to the modulators. This amplitude difference is subsequently utilized, through an arrangement of filters and rectifiers, to produce right-left deflection of a CRO tube trace and to actuate the BDI pen of the range recorder.

The Range Recorder

Target range is indicated in the modified receiving rack by means of a two-pen chemical recorder (Figure 4) which also presents a graphic record of the right or left deviations of projector bearing. In this recorder, moist electrochemically sensitized paper is withdrawn at constant speed from a closed container by means of two geared steel rollers. A carriage, to which two electrically separated styli are attached, is driven periodically from left to right across the paper at right angles to the paper's motion. The styli, by feeding electric current through the moist paper to a steel idler roller, produce visible traces whose density varies in proportion to the amount of current passed.

The carriage is moved from left to right by a cord wound on a pulley and driven, through a magnetic clutch, by a synchronous motor and gear arrangement which is also utilized to move the paper rollers. Electric contacts are mounted on the carriage to key the outgoing pulse at the beginning of the stylus transit, and to de-energize the magnetic clutch of the carriage drive at the end of the cycle. As the carriage is drawn from left to right, light helical springs on its track are compressed and serve to return the carriage rapidly to its starting point when the magnetic clutch is de-energized.

Two paper speeds and two carriage speeds are available through the synchronous motor and gearing arrangement. The fast speed accommodates ranges up to 1,500 yd and the slow speed is used for longer ranges between 1,500 and 3,750 yd. In addition, the carriage "fly-back" contacts may be moved to the right or left on the recorder chassis to regulate the length of travel of the carriage and permit it to be returned for the start of a new cycle as soon as the echo is received.

Echo signals from the right and left projector halves differ in phase if the projector is not accurately on the target bearing. This phase difference is converted, by means of the BDI circuits (see Section 5.2.1) into a difference in amplitude between two signals having different frequencies. These signals are fed into separate rectifiers at the recorder. One side of the output of each rectifier is connected to a separate stylus. The steel roller beneath the paper forms a link in a common ground return path to the rectifiers so that current flows through the paper from the styli. Since the intensity of the trace varies with the amount of current flowing through the paper, a difference in magnitude of the rectified signals will result in differences in the trace densities. As the two styli are slightly offset from each other in range, an indication of right or left deviation of the projector bearing is obtained from the position of the darkest echo trace. Range scales are calibrated so that the location of the echo trace indicates the target range directly in yards.

Oscilloscopic Presentation

The echo pattern and right-left indications are presented in the Mark II rack by means of a single cathode-ray oscilloscope having a long-persistence screen. The apparently simultaneous presentation of the two traces is effected by use of an electronic switch which permits the CRO to be used for the echo pattern and the right-left indications on a shared-time basis. An increase in the deflection of the right-left indicator trace may mean either that the target bearing error has increased or that the echo giving the indication is of greater intensity than a preceding echo from the same target. The measure of echo intensity given by the oscilloscope aids, therefore, in interpreting the BDI trace. A typical echo pattern and right-left trace is shown in Figure 5.

Time Variation of Gain

Time variation of gain is effected in the modified equipment by the use of a simple electrical network (see Section 2.2) which causes the amplification to increase from a very

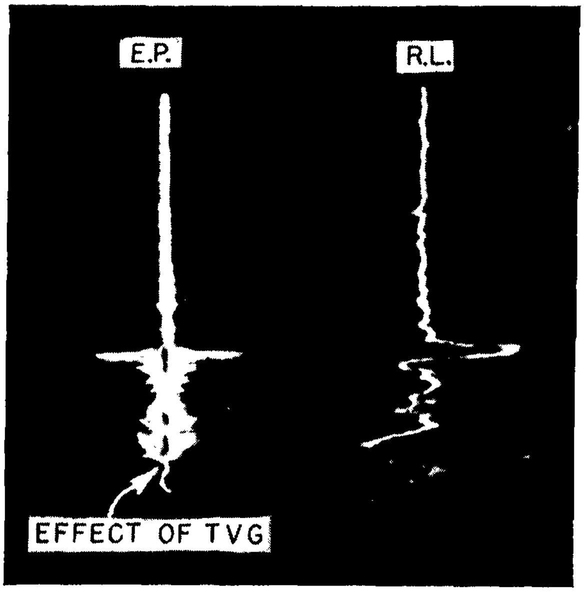


FIGURE 5. Appearance of CRO screen showing typical echo pattern and right-left trace.

low value, at the initial stage of the receiving cycle, at a rate compensating approximately for loss of echo strength with range. The use of this circuit, by reducing the formerly high initial reverberation level, minimizes listening fatigue and eliminates overloading of the visual indicators without impairing response to real targets.

PANEL ILLUMINATION

The use of a cathode-ray tube on the console of the modified receiving rack limits the brightness of illumination desirable for the bearing dials and for the range recorder. In the Mark II rack the engraving of the bearing dials and pointers is filled with fluorescent material and illuminated by ultraviolet light. Suitable optical filters at the light source prevent visible light from reaching the dials and also prevent the escape of ultraviolet radiation from the panel. This avoids possibility of injury to the operator's eyes and also excitation of the CRO screen.

Range graduations are shown on the recorder by translucent scales under the record paper. By means of light filters the correct scale is automatically selected by the switch which controls the gear ratio of the recorder. Illumination levels of all dials and instruments are balanced to reduce eyestrain.

6.4.1 Tests

In the installation of Mark II racks on sound school vessels, provision was made for comparative tests between the original echo-ranging receiving equipment and the modified racks. Thus it was easy to obtain an effective comparison of the two equipments.

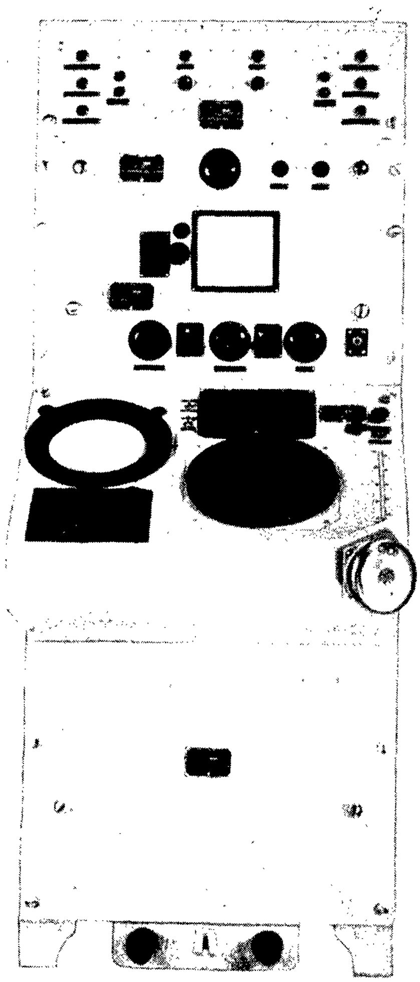


FIGURE 6. Submarine signal company production unit QGA receiving rack.

It was found that the MTB feature of the new rack made it possible to obtain two to three times as many echoes, in the period just following first contact, as were obtainable in the same period with relative bearing training. Similarly, the tests indicated that at least twice as many echoes per unit of time were obtainable as a result of the BDI feature. In addition, the rapidity with which a new operator was able to learn to operate the equipment was markedly greater with the new arrangement.

As a result of these tests, the convenient console layout, MTB, BDI, TVG, the increased accessibility, and the range recorder were considered worthwhile improvements. On the other hand, the echo pattern trace on the oscilloscope, the dual pen on the recorder for right-left indications, AVC, and the bearing dial with interchanged true and relative bearing scales were considered to be undesirable or of doubtful value.

6.4.2 Production Models

The need for complete new echo-ranging systems for installation on new ships was so urgent by the time the Mark II rack was completed, that this unit was not used as a preproduction model as originally intended. Instead, the Navy requested two manufacturers to develop complete new equipment incorporating most of the Mark II receiving rack features. The resulting production units, QGA and QGB (Figures 6 and 7), retained the features of console-type arrangement, MTB, BDI, the use of a recorder to indicate range, TVG, and easy accessibility for inspection and maintenance, first incorporated in the Mark I and Mark II models.

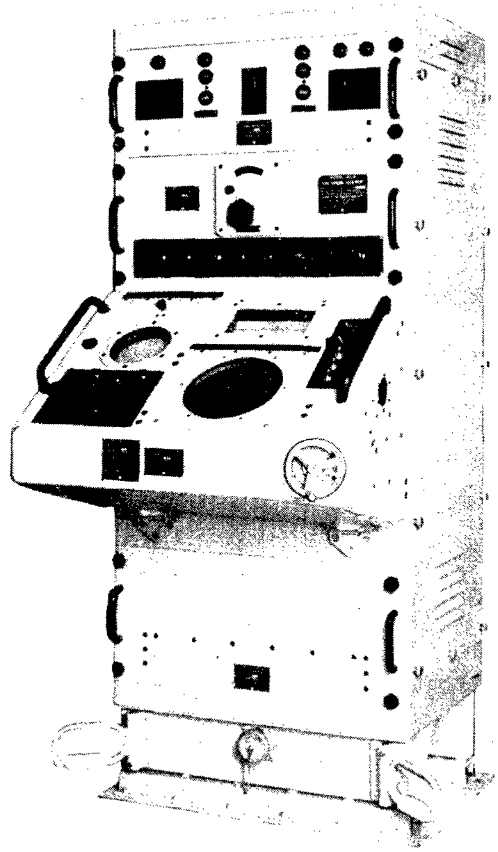


FIGURE 7. RCA manufacturing company production unit QGB receiving rack.

Chapter 7

ANCHORED VESSEL SCREEN

7.1 INTRODUCTION

Anchored vessel screen [AVS] was developed as a means of protecting ships at anchor from miniature submarines and small manned torpedoes. Because of the small amount of noise generated by these objects, direct listening was ineffective. Previous echo-ranging equipment was not suitable for the detection of nearby bodies of such small size.

The problem was to produce a small high-frequency echo-ranging device which would be as nearly automatic as possible. This should present to a relatively unskilled operator a continuous picture of the location of all underwater objects, down to the size of a 3-ft sphere, which are not over about 300 yd distant or 60 ft deep. The precision in azimuth should be about 10 degrees.

The problem was attacked independently by the Bell Telephone Laboratories [BTL] and the Harvard Underwater Sound Laboratory [HUSL]. Each group produced a model which received preliminary tests, but the need for the device passed and the AVS project was therefore dropped before a final design was reached by either laboratory.

The BTL model (AVS Mark III) involved no moving parts, but it contained rather extensive electronic circuits. A short pulse of 32-kc sound was projected in all directions in the horizontal plane. A returning echo was received by a group of five crystals in a horizontal square array. Since each of these crystals was, in general, at a different distance from the target, each received the sound in a different relative phase. By proper comparison of these phases, the bearing of the target could be determined. The range could then be deduced as usual from the echo time delay. Actually, in this design the voltages from the various receiving crystals and from the timing circuit were combined in such a way as to automatically produce a pair of voltages proportional to the x and y components of the radius vector to the target. When these output voltages were applied to the x- and y-deflection plates of a cathode-ray tube, the cathode-ray oscilloscope [CRO] screen presented a map of the region around the ship with a bright spot in the relative position of the target.

In the HUSL model, the CRO screen gave a similar map of the surrounding territory, but by more mechanical means. A directional transducer was rotated by a motor back and forth between two adjustable limit switches, thus scanning any desired sector around the ship. A deflecting coil on the CRO was rotated in step with the transducer by a mechanical linkage between the two. The magnitude of the deflection produced by this coil was governed by an electronic sweep circuit which moved the beam radially outwards starting from center at each ping. Thus an echo produced a bright spot on the screen at a position corresponding to the target in both bearing and range. Audible indication was also provided in this model.

Anchored Vessel Screen Mark III (BTL)

Anchored vessel screen [AVS] Mark III, developed by BTL, is an echo-ranging system developed for protection of anchored vessels from small submarines and manned torpedoes at a range adequate for defensive action. It consists essentially of (1) a projector radiating vertically directional pulses over 360 degrees of azimuth, and (2) a directional hydrophone arranged as a double dipole to give azimuth bearing scanning for target echoes received over 360 degrees. A PPI screen presents a ship-centered map of relative target position. Although models indicated that, with modifications, the instrument presented a satisfactory solution to the problem, the project was discontinued in the interest of other projects carrying higher priorities.

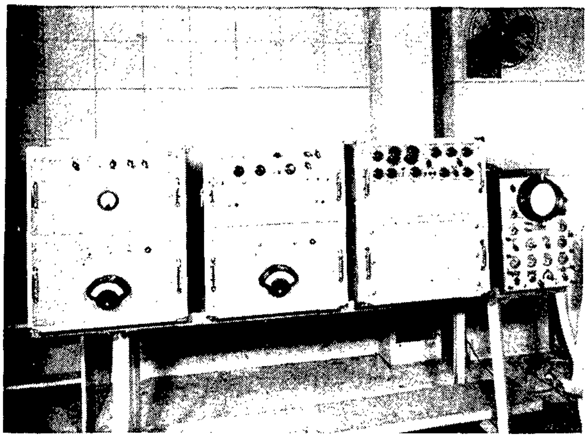


FIGURE 1. Laboratory model of the AVS Mark III, electronic equipment, front view.

7.2 GENERAL DESCRIPTION AVS MARK III

Separate projector and receiver units are provided in the BTL version of AVS. The projector consists of a vertical array of crystal units, a line about six wavelengths long. It sends out short periodic pulses of sound rather uniformly in all directions. The receiving hydrophone consists of a nondirectional unit and two dipoles at right angles to each other. These feed through separate amplifier channels whose relative outputs are thus a function of the bearing of the target. This information, together with information on range, is then given plan position indicator presentation on the screen of a cathode-ray oscilloscope.

The presence of a target is indicated by a bright spot on the screen, its position being an immediate indication of the location of the target. Furthermore, the brightness of the spot is an indication of the size of the target.

The equipment was designed to operate at 32 kc—sufficiently above that of standard sonar systems to avoid interference, and yet near enough to make use of the knowledge already available in this region.

7.2.1 Dipole Theory

The receiving hydrophone consists of a nondirectional unit and two dipoles at right angles to each other. The manner in which such a dipole-type hydrophone is able to supply information on bearing can be understood by reference to Figure 2.

Five receiver units, disposed as shown in the figure, provide two dipoles, one along each diagonal of a square, and a reference unit at the center of the square. If sound of wavelength twice the length of the diagonal arrives from a source in the same plane as that of the receiver

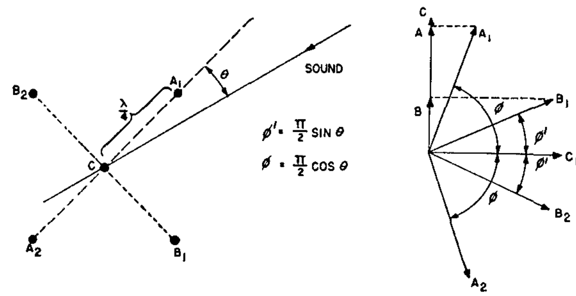


FIGURE 2. AVS Mark III, special hydrophone layout and vector diagram with resulting electrical signals.

units, a simple relation can be deduced between the resulting electrical signals and the direction of the source.

Let sound arrive from the direction ϕ with respect to the diagonal A_1A_2. Let ϕ be the difference between the phase of the sound at C and at A_1 (or A_2), and ϕ the difference between that at C and at B_1 (or B_2). Then,

$$\phi = \frac{\pi}{2} \cos \theta \tag{1}$$

$$\phi' = \frac{\pi}{2} \sin \theta .$$

The electrical signal for each dipole is obtained by electrically connecting the two members of the dipole in parallel opposing, thereby distinguishing against sounds arriving in the vertical direction. The voltage output of a pair of identical a-c generators connected in this manner will be half the vector difference between their individual voltages.

The vector diagram of Figure 2 shows the resulting electrical signals. The vectors A_1, A_2, B_1, B_2, and C_1 represents the signals from the respective units. The vector A which is half the difference between vectors A_1 and A_2 represents the output of dipole A_1A_2. Likewise B is the output of dipole B_1B_2. It will be noted that the two dipole signals are always 90 degrees out

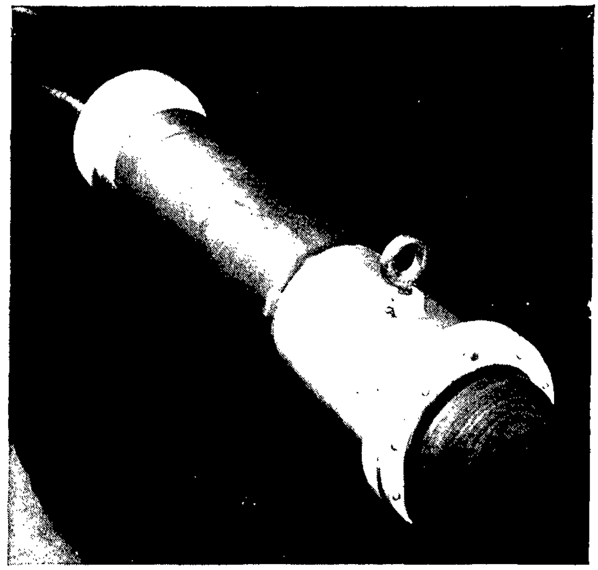


FIGURE 3. AVS Mark III projector and receiver assembly.

of phase with the signal from the C unit and either in phase or out of phase with each other depending on the direction of the source. As will be pointed out later, the signal C_1 is shifted 90 degrees in the amplifier, thus yielding the vector C in the figure. Theoretically, C is nondirectional. The amplitudes of A and B as a function of direction are

$$A = A_1 \sin \frac{\pi \cos \phi}{2},$$

$$B = B_1 \sin \frac{\pi \sin \phi}{2}.$$

Furthermore, $A_1 = B_1$ for the case of identical receiver units.

Now, if the x and y deflections of a CRO electron beam are made proportional to signals A and B respectively, the angular position ψ of the CRO spot with respect to the x axis will be approximately equal to ϕ. More precisely, the angle will be

$$\psi = \tan^{-1} \frac{\sin (\pi/2 \sin \phi)}{\sin (\pi/2 \cos \phi)} \qquad (2)$$

which deviates from ϕ by no more than ± 8 degrees in each 90-degree quadrant.

7.3 DETAILS OF AVS MARK III

7.3.1 The Transducer

A photograph of the cylindrical transducer assembly is shown in Figure 3. The assembly includes (1) a line projector unit mounted along the axis of the cylinder somewhat above the middle, and (2) a receiver unit mounted at the bottom face down. Both units are bathed in castor oil and are provided with ρc rubber windows. The entire assembly is about 40 in. long, 6½ in. in diameter and weighs about 120 lb. It is designed to hang with its axis vertical.

THE PROJECTOR UNIT

A considerable amount of experimentation was required to obtain a projector design which

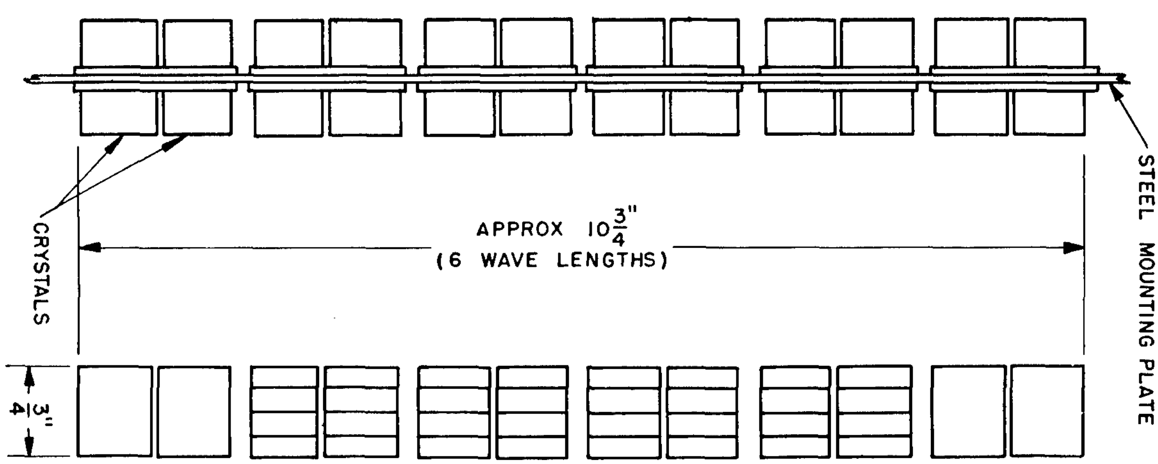


FIGURE 4. Crystal layout of two-line projector in AVS Mark III.

would provide a beam with uniform horizontal distribution and at the same time have a suitable mechanical structure. The crystal layout of the second completed experimental model is shown in Figure 4. Quarter-wavelength 45-degree Y-cut Rochelle salt crystals are mounted back to back in two vertical lines on a mounting plate, the structure being designed to resonate in water at 32 kc.

The power which can be radiated continuously by a projector of this area, without cavitation or damage to crystals, is about 25 watts. However, for short intermittent pulses it was found that much more power could safely be radiated—about 600 to 700 watts for 2- to 3-msec pulses at ½-sec intervals.

The variation in response of the projector with elevation is shown in Figure 5. Its sensitivity is more than 10 db down at angles 10 degrees from the horizontal, and side lobes are not less than 15 db below the main lobe.

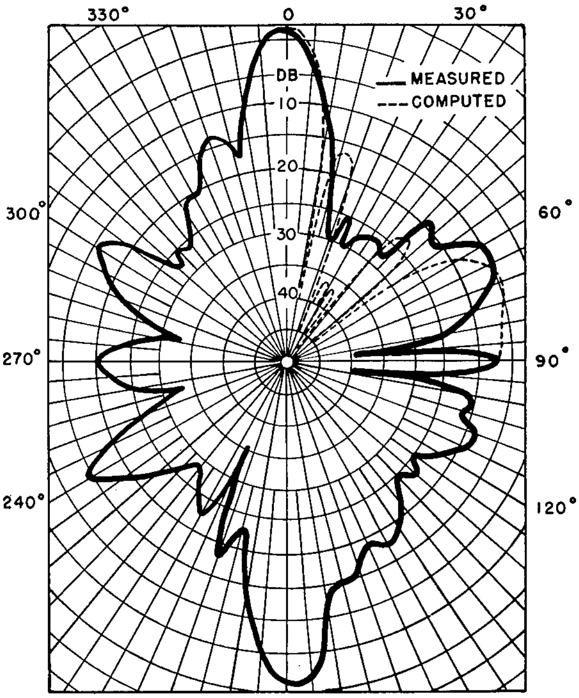


FIGURE 5. AVS Mark III, projector directivity in vertical plane.

Measured response of the projector in the horizontal plane shows a variation of ±5 db from the desired uniform omnidirectional characteristic.

The Hydrophone Unit

Resonated quarter-wavelength 45-degree Y-cut Rochelle salt crystals are also used for the receiving unit. The assembly drawing of Figure 6 shows the layout of the crystals. They are arranged in a square about 1.1 in. to the side and organized into five units, a central unit about 0.5 in. square and four others, one at

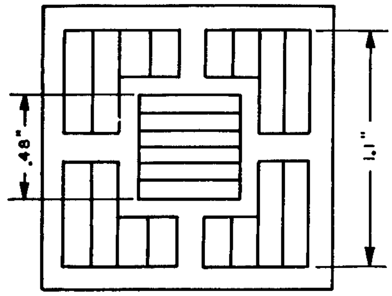


FIGURE 6. Crystal layout for the double dipole hydrophone, AVS Mark III.

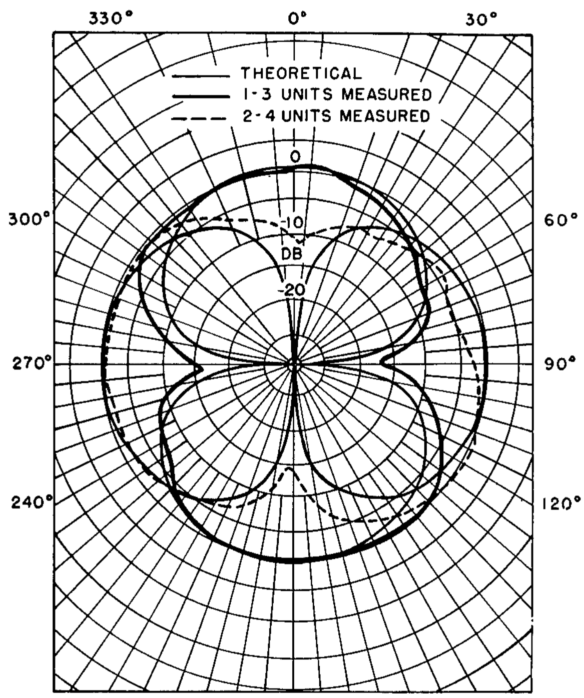


FIGURE 7. Horizontal directivity of hydrophone dipoles, AVS Mark III.

each corner of the central square. Each pair of diagonally opposite units constitutes one of the dipoles. The distance between the effective centers of these units is about one-half wavelength for 32 kc radiation in water. The entire unit thus approximates the theoretical array discussed in connection with Figure 2.

Figure 7 shows how the actual directivity of the electrical signal from the two dipoles compares with the theoretical value deduced above for such an array [equation (1)]. Figure 8

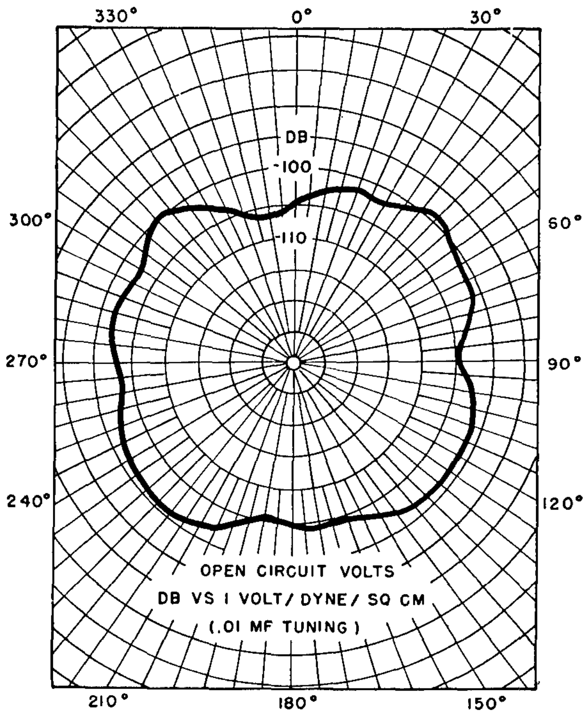


FIGURE 8. Horizontal directivity of hydrophone C unit, AVS Mark III.

shows how nearly the electrical signal from the C unit approaches the desired nondirectional characteristic.

7.8.2 Electronic Equipment

Figure 1 is a photograph of the equipment used in conjunction with the above transducer. This equipment consists of a transmitter and timing circuit, test set, receiver, and oscilloscope. Figure 9 illustrates by means of a functional schematic diagram the operation of the various components. Detailed circuit diagrams may be found in the AVS completion report.[1]

Timing Circuit

The timing circuit (housed with the transmitter unit) controls electronically the sequence of operation of the various features of the system. A typical sequence is shown in Figure 10. A primary pulse disables the receiver and blanks the CRO for 150 msec out of each 550-msec period. The transmitter is triggered 50 msec after the receiver has been disabled. The duration of the transmitted pulse may be varied from about 0.1 msec to about 21 msec and is also determined electronically. Finally, the timing circuit provides a *time variation of loss* [TVL] voltage which is used to vary the gain of the receiver-amplifier with time. This voltage is held constant during each 150-msec period the receiver is disabled and then increases so as to provide increase in gain at a predetermined rate during the following 400 msec. Since the 400-msec period during which the receiver is enabled begins 100 msec after the transmitted pulse is sent out, the receiver is in condition to receive echoes from targets in a range of 80 to 400 yd.

Transmitter

The 32-kc transmitter was designed to produce power at the rate of 100 watts for 10-msec pulses twice each second. It is of the multivibrator type, normally disabled. Its frequency is controlled by a 128-kc master oscillator (mounted on the test panel) which is in continuous oscillation.

Test Set

Artificial echoes are available from the test set to simulate operating conditions. Two echoes can be produced, the two being entirely independent as to their time delays (range) and bearings.

Receiver

The receiver consists essentially of three amplifier channels, *A*, *B*, and *C* for the three similarly designated hydrophone units, plus

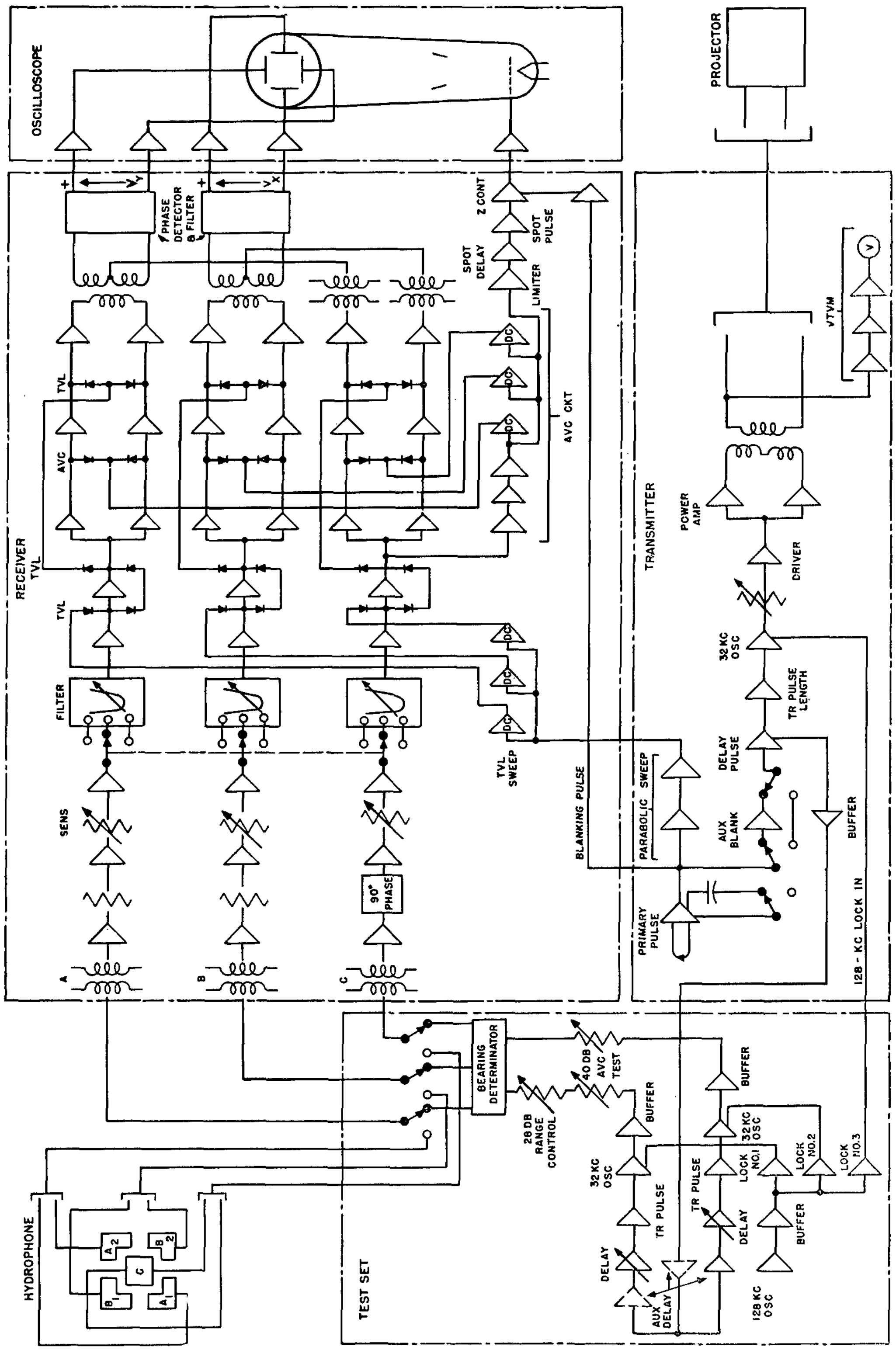


FIGURE 9. AVS Mark III, functional schematic diagram.

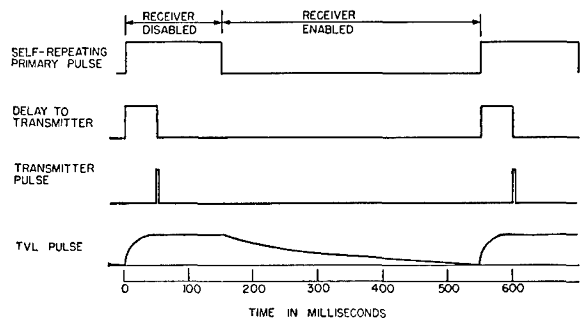


FIGURE 10. Typical timing sequence, AVS Mark III.

the associated TVL, *automatic volume control* [AVC], and Z (oscilloscope gain) control circuits. As is indicated in Figure 9, each of the three channels is an eight-stage amplifier (the final few stages, push-pull), including in sequence two stages that are TVL-controlled, one AVC-controlled and a final one that is TVL-controlled. A variable band-pass filter is inserted between the third and fourth stages of each channel. Furthermore, a 90-degree phase shift is introduced into the *C* channel (between the first and second stages), so that the output signals from the *A* and *B* channels will be in phase (or exactly out of phase) with that of the *C* channel. The outputs of the *A* and *B* channels are combined individually with that of the *C* channel and yield two voltages which are used to determine the x and y CRO deflections. The position of the CRO spot becomes an indication of the location of the target.

TVL and AVC Control. The TVL- and AVC-controlled stages employ copper oxide varistors as circuit elements. Direct currents are supplied to these varistors by separate current amplifiers (labeled *DC* in Figure 9) and the magnitudes of these currents are controlled by the AVC voltages. Since the impedance of a varistor (to alternating current) is a function of the direct current flowing through it, the gain of each amplifier stage affected becomes a function of the associated control voltage. The impedance of a varistor is also a function of temperature and hence the entire receiver is temperature controlled (at about 110 F).

The TVL sweep voltage is designed to increase the gain of the first two TVL-controlled stages with time in such a manner as to balance out decrease in signal strength with target distance. Thus, if all targets were the same size and equal in reflecting ability and if there were no multiple paths to consider, at the output of the second TVL stage the amplitudes of the signals would be independent of target distance. However, different intensities of echoes will be obtained because of variations in these factors.

The function of the AVC stage is to eliminate these variations and thus produce a signal which is independent of target size as well as range. The AVC voltage is derived from the nondirectional *C* channel, but is applied to all three. Inasmuch as the duration of the sound pulse is short, the AVC circuit is designed to produce its full range of control (about 30 db) in about 0.1 msec.

The final TVL-controlled stage reintroduces the distance concept by again providing gain that increases with time. This yields output signals which, when applied to the oscilloscope, produce deflections proportional to target distance.

Phase Detector and Filter. The original signals from the two receiver dipoles have a relative magnitude and phase which depend on target bearing (see Figure 2). This relationship is preserved throughout amplifier channels *A* and *B*. Hence the final output will contain information on target bearing as well as on target range.

The phase detector and filter are designed to pass this information on to the oscilloscope in intelligible form. A part of the detector circuit is shown in Figure 11. The output of each of

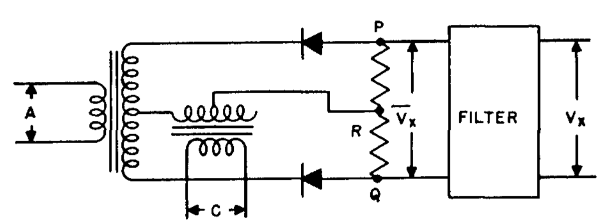


FIGURE 11. Phase detector circuit, AVS Mark III.

the two channels *A* and *B* is combined with that of the nondirectional channel *C* by means of a bridge-rectifier-type detector to yield, after filtering, two d-c voltages, V_x and V_y, whose relative magnitudes and signs are dependent on

target bearing and whose absolute magnitudes are proportional to target distance. These voltages determine the position of the cathode-ray beam.

Z-Control Circuit. The Z-control circuit determines the voltage applied to the control grid of the cathode-ray tube and hence controls the brightness of the CRO spot. It utilizes the blanking voltage from the timing circuit to disable the oscilloscope while the sound pulse is sent out (and for 100 msec thereafter). When an echo is received by the *C* hydrophone, the resulting pulse in the AVC circuit is used to enable the oscilloscope for the duration of the echo, after a short delay which first allows the beam to move to its correct position. Furthermore, since the AVC voltage is a function of target size, the brightness of the CRO spot becomes an indication of target size.

OSCILLOSCOPE

A standard Dumont 175A oscilloscope was modified for use with this equipment. The principal change involved the substitution of a high-persistence-type 5CP7 tube for the standard cathode-ray tube. The face of the tube is provided with a scale calibrated in terms of target coordinates. The bearing scale actually realized departs from the theoretical scale of equation (2) by as much as 12 degrees and, in fact, is ambiguous over one 20-degree sector. This is due primarily to the fact that the directivity patterns for the projector and the receiver dipoles themselves (Figure 7) departs somewhat from the patterns desired.

7.3.3 Performance Tests

When laboratory tests with the synthetic echoes from the test set indicated that the many and diverse circuit problems were about solved, the entire system was taken to sea for trial with real echoes. Tests were made in 100 ft of water using a 3-ft sphere as target.

The projector-hydrophone was hung about 10 ft below the surface of the water—a suspension which proved to be quite unsatisfactory. The unit could not be kept vertical or stable and it was probably too near the surface. Very few tests were made, but enough to indicate the need for a number of changes in the projector and electronic equipment to overcome effects of reverberation.

The AVS project was terminated when the urgent need for its development had subsided. Consequently, such changes were never made. However, it was believed that a system along the lines proposed could be made to work—at least under favorable conditions of surface and bottom reverberation.

7.3.4 Recommendations

Several proposals for improving the operation of this equipment were worked out but never put into effect. One of these involved a 4-line vertical projector whose proposed structure and crystal layout[1] was designed to produce a sound beam more uniform in the horizontal plane and narrower in the vertical plane. This, in turn, would make a complete redesign of the driver circuits, as well as the timing and pulse circuits necessary.

Such modifications would call for rather extensive changes in the original experimental design and would require electronic circuits of complexity beyond even that of the experimental model just described.

Anchored Vessel Screen (HUSL)

Anchored vessel screen [AVS] is a semiautomatic echo-ranging system designed for the protection of anchored war ships from miniature submarines and manned mines. The equipment operates as an acoustic analogue of search radar, each bearing being searched successively in range. The operating frequency (above 60 kc) and pulse length (2, 8, or 16 msec) are chosen to provide effective operation with small targets. It consists of (1) a directional transducer made to scan automatically any designed sector around the ship, and (2) electronic circuits which, in addition to the audible echoes of conventional echo-ranging procedure, provide visual indications obtained by allowing the echo signal to

brighten a spot on the screen of a radial-scan PPI oscilloscope so as to represent the range and bearing of the target. Although the two models constructed operated according to expectations, the work was suspended in favor of higher priority programs, and the AVS was never put into actual production. Development of this AVS equipment was carried on by HUSL.

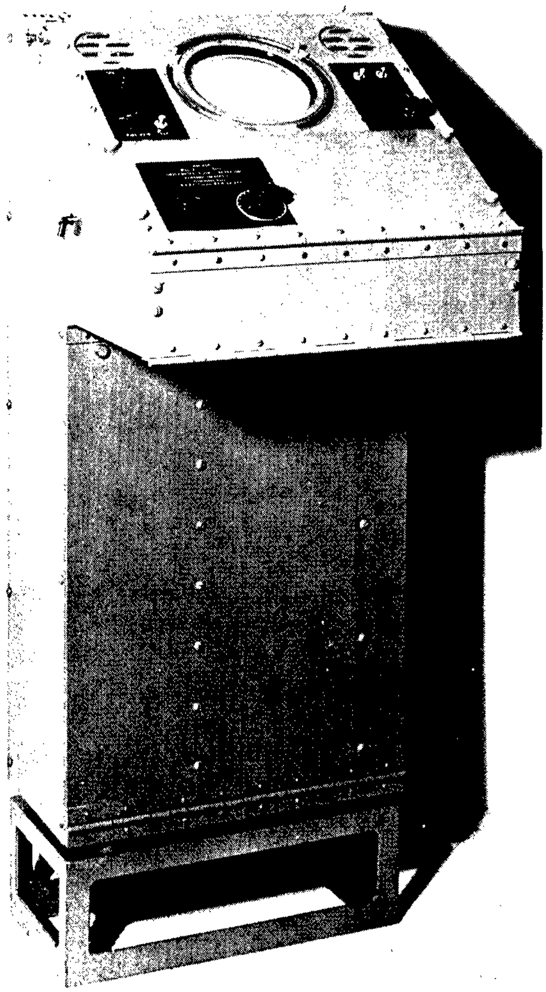


FIGURE 12. Front view, AVS Model II console.

7.4 DESIGN CONSIDERATIONS

In adapting echo-ranging equipment which uses a single transducer to the function of automatic search, the shape of the sound beam (i.e., the sensitivity pattern of the transducer) and the desired maximum range together determine the maximum rate at which the projector can be rotated and still provide effective coverage.

The velocity of sound in water determines the optimum rate of pinging for any desired range. The projector must not be rotated too far between pings or the echo from a target will fall upon its diaphragm at such an angle that sensitivity in the direction of the target is below that required for detection. For instance, consider a transducer 4 in. wide having a beamwidth of 15 degrees (3 db down) at 75 kc. For a range of 400 yd, 2 pings each second are specified. Thus, rotating the transducer at 15 degrees per second will produce effective coverage of the desired area each 24 sec.

The effects of frequency and ping length also require some analysis. Use of a higher frequency than that of conventional echo-ranging equipment was suggested by the fact that small objects are better reflectors of short waves than of long ones. However, the rise of attenuation with increasing frequency is a limiting factor. In the case of ping length, shorter pings provide a better signal-to-reverberation ratio and a more precise location of target. On the other hand, a pulse of sound must have a certain minimum length for the average ear to detect it. The optimum adjustment depends on the particular equipment used and can best be determined by experiment.

7.5 AVS MODEL I [HUSL]

7.5.1 General Description

In this AVS system, simple mechanical coupling between the shaft of an echo-ranging transducer and the deflection coil of a CRO system was used to coordinate the angular position of the cathode-ray beam with that of the sound beam. The projector was made to train back and forth about its vertical axis by means of a reversing motor. Adjustable limit stops defined the arc of this automatic search.

The projector used was a Rochelle-salt crystal transducer with a single 4x4-in. face, operable over the frequency range 60 to 80 kc. When mounted in its cylindrical steel housing, its

measured pattern was 25 degrees wide (10 db down) at 65 kc.

The transmitter circuit was of the "duty-cycle" type, providing high peak output power of short duration but requiring low average input power. Receiving-type tubes were used throughout. Both pulse length and pulse interval were controlled by a synchronous motor-driven cam arrangement.

The receiver circuit was of the superheterodyne type and incorporated *time-varied gain* [TVG] (see Section 2.2). Its output provided both the voltage for the brightening grid of the cathode-ray oscilloscope and, through an audio amplifier, the audible signal for the loudspeaker.

7.5.2 Performance

This first model gave very promising overall performance. Good echoes and indications on the oscilloscope screen were obtained regularly from buoys having effective dimensions of 2 x 6 ft at distances of 300 yd, and occasionally at 400 yd and more.

Simple mechanical coupling between the transducer and the CRO system proved to be quite satisfactory. So also was the mechanical system used for timing the pulses. However, the mechanical arrangement for determining pulse length would not produce satisfactory pulses shorter than about 4 msec.

7.5.3 Recommendations

Reverberation was an ever-present source of interference. Particularly in shallow water, bottom reflections often masked the desired echo. This indicated the desirability of using a projector with a narrower vertical beam. In attempting to reduce reverberation by decreasing pulse length it was noted that echo strength was also diminished. With the receiving system incorporated in this first model, it did not appear that any advantage could be gained by shortening the pulse below about 10 msec. Nevertheless, it was decided to devise an electronic method for determining pulse length so that shorter pulses could be tried with a modified receiver. To eliminate overshooting and undesirable transients introduced into the power line when the motor was reversed, it was further suggested that a clutch-reversing mechanism be designed for reversal of training in the next model.

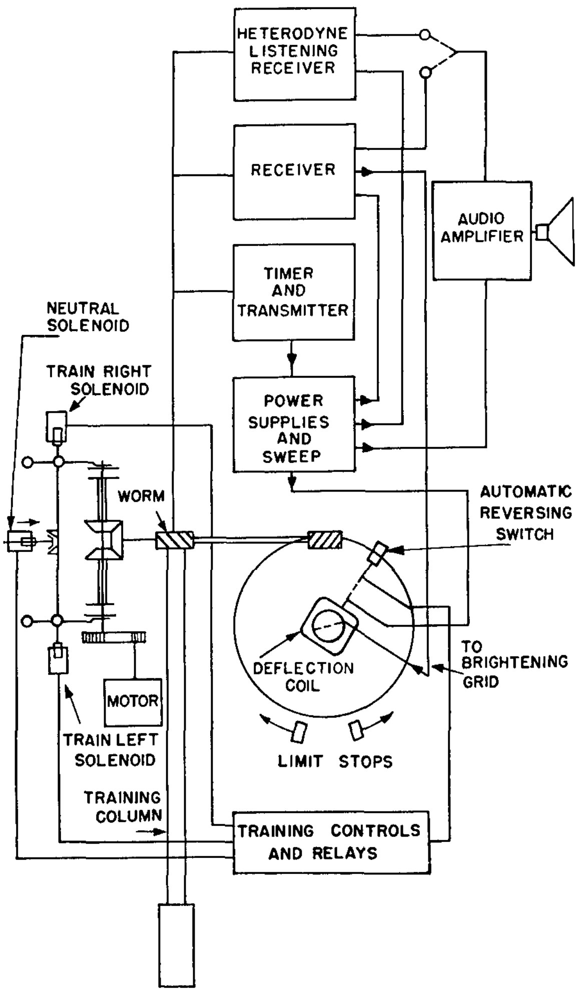


FIGURE 13. Block diagram of AVS Model II.

7.6 AVS MODEL II [HUSL]

7.6.1 General Description

Model II AVS duplicates the features of the first model in most respects; however, it introduced several improvements. The block diagram of Figure 13 shows the general arrangement of the components. The front and rear views of the unit, exclusive of projector,

are shown in Figures 12 and 14, respectively.

The echo-ranging projector searches automatically back and forth over any selected sector. Echoes from a target produce an audible signal in the loudspeaker and mark the location of the target as a brightened spot on the CRO. The cathode-ray beam, adjusted to be near the threshold of visibility, is moved radially outward by means of deflecting coil and an electronic sweep circuit, starting from center at

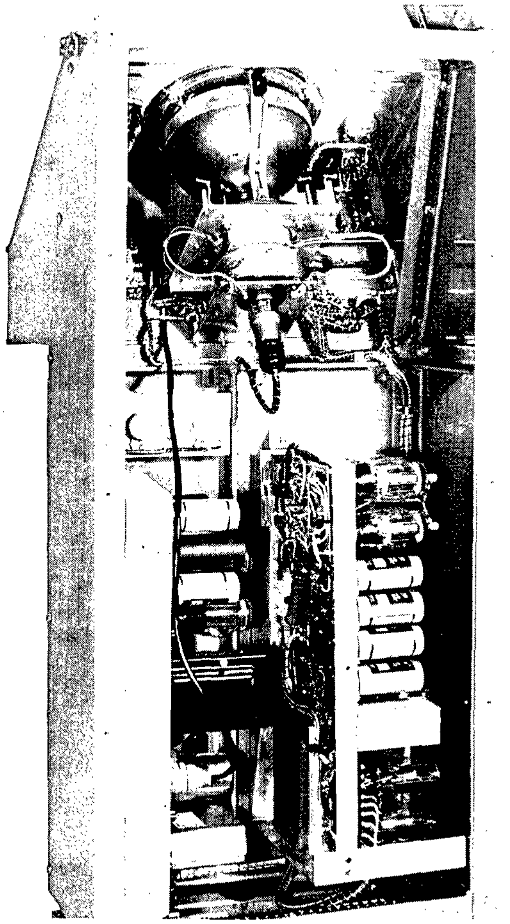


FIGURE 14. Close-up rear view, AVS Model II.

each ping. The angular position of the cathode-ray beam is synchronized with the bearing of the projector by means of direct mechanical coupling between the vertical shaft of the projector and the CRO deflection coil.

Four major departures from the first model are incorporated in Model II. They are (1) a specially designed console for housing the equipment, (2) a projector having a narrower vertical beam, (3) a clutch-operated reversing mechanism replacing the reversing motor, and (4) an entirely new electronic chassis with modified circuits, including electronic control of pulse length. In addition, Model II includes a separate receiver designed for underwater listening. Provision is also made for searching over either an 800- or a 400-yd range by pinging either once or twice each second. Training of the projector may be controlled either automatically or by means of a manually operated switch.

7.6.2 Details of AVS Model II

CONSOLE

The console houses the various electronic chassis, each component being easily accessible for checking and servicing. The CRO tube, loudspeaker, and controls are mounted conveniently at the top of the console, with the face of the CRO tube located at the center of the main panel. Surrounding the tube is a relative-bearing scale over which a pointer moves to show the direction of the sound beam at all times. This pointer is attached to the deflection coil and thus rotates with the projector shaft. In a circular slot located outside the relative-bearing scale are two sweep-limit stops which may be adjustable to limit the sector to be searched. The maximum sector through which a search may be made is approximately 300 degrees excluding the after direction.

The unit operates at 110 v, 60 c and requires a total of 250 w with the training motor in operation. A filter is included in the power line for removing line noise.

PROJECTOR

The projector is a Brush Type C-26 Rochelle-salt unit with a 3x12-in. radiating surface. Pertinent pattern data obtained on this projector as used, mounted inside its cylindrical housing so that it was working through a 0.020-in. steel window, are given in Table 1.

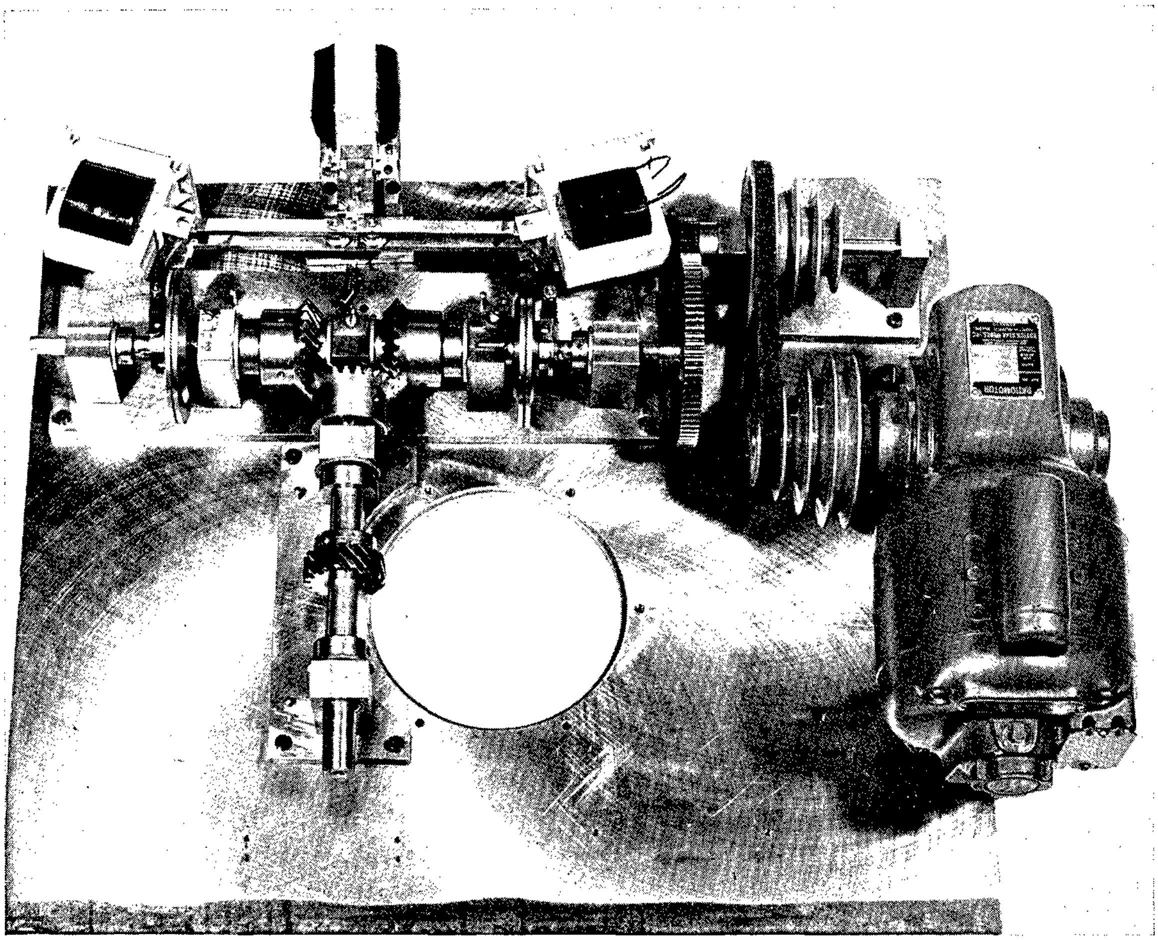


FIGURE 15. Motor, gear and clutch assembly for training transducer, AVS Model II.

TABLE 1. Pattern data on Brush Type C–26 projector.

	Horizontal		Vertical	
Freq. (kc)	Width of major lobe 6 db down (degrees)	Decibels down to minor lobe	Width of major lobe 6 db down (degrees)	Decibels down to minor lobe
60	26	15	7	16½
65	25	13½	7	17
70	22	12	6	17+
75	23	13½	6	20½
80	17	14	7	22

PROJECTOR TRAINING

The mechanism used for training the projector in Model II is shown in Figure 15. A motor with speed-reducing gears works through a belt drive into another set of gears matched to obtain a final rotation speed of 14 degrees per second. Mounted freely on the drive shaft are two bevel gears, each with a clutch face attached. Paired with each of these clutch faces is a face driven by the drive shaft. A mechanical linkage between the two clutches prevents simultaneous engagement of both clutches. Clutch action is controlled by three solenoids, with the neutral position automatically assumed when none of the solenoids is energized. The electric circuits provide for either automatic or manual training. Solenoid circuit diagram and description of operation are given in the AVS completion report.[2]

ELECTRONIC CIRCUITS

The Transmitter. Incorporated in Model II is a blocking oscillator type transmitter (see Figure 16) which permits large power output for short time intervals, with a moderate power drain. The output voltage across the C-26 transducer is approximately 270 rms volts.

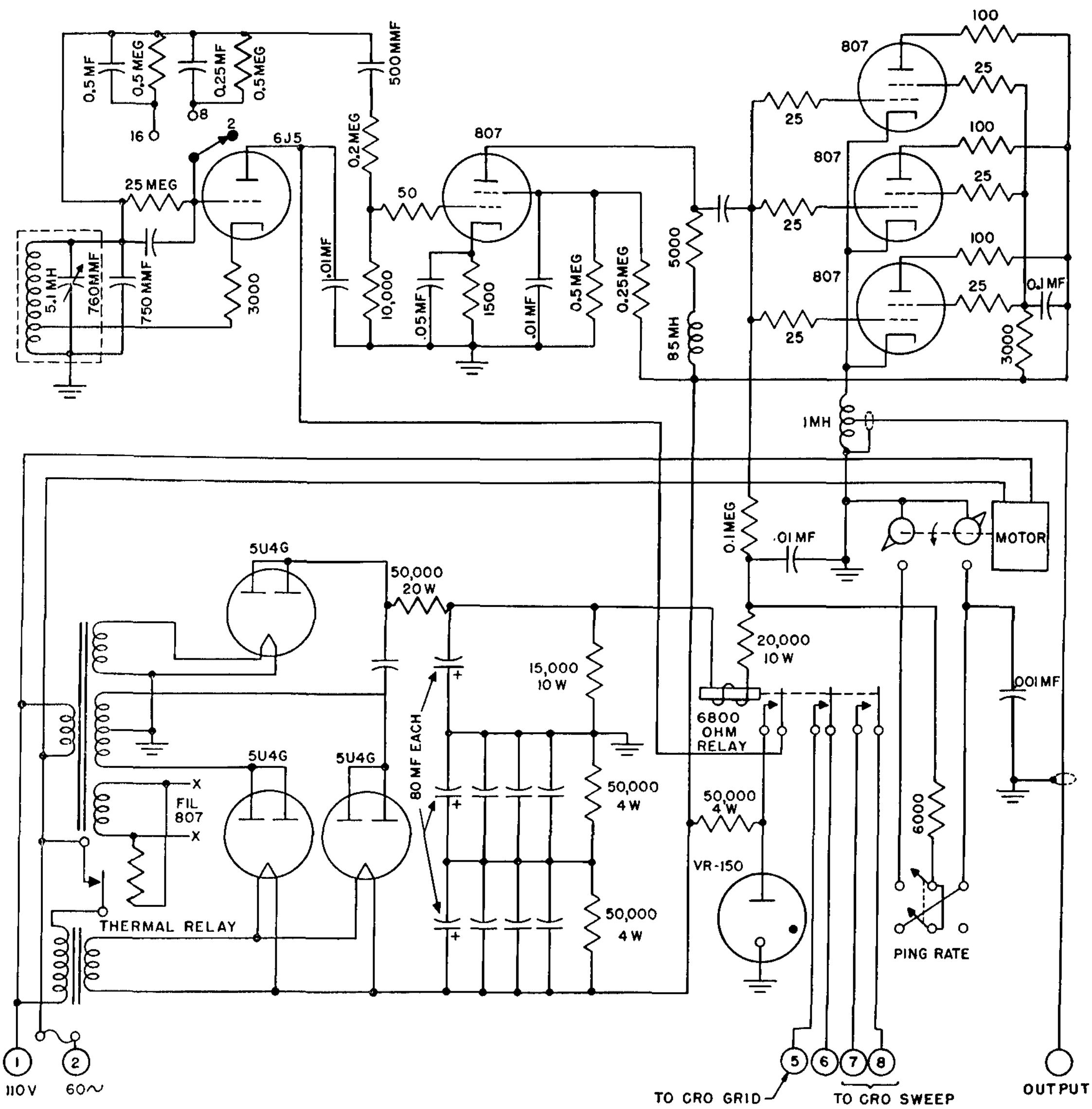


FIGURE 16. Transmitter circuit, AVS Model II.

A 6J5 tube, with its plate voltage regulated by a type VR-150 voltage regulator, serves as oscillator. The plate circuit of the oscillator is completed through relay contacts actuated by a keying cam. The oscillator signal is amplified by a stage of voltage amplification which uses a single type 807 tube, and by a final stage which uses three type 807 tubes in parallel. These operate as a cathode-follower amplifier, with the cathodes connected through a small inductance to ground. Output power is obtained from the cathode circuits. During the nonoperating period several hundred volts of bias are applied to the output stage so that its grid potential is well beyond cutoff.

When the oscillator is keyed, the 807 bias is simultaneously dropped to a value which barely permits grid current to flow. Thus extremely heavy plate-current surges occur during the short transmission pulses, but the average current is low. High-capacity filter condensers in the high-voltage power supply minimize the

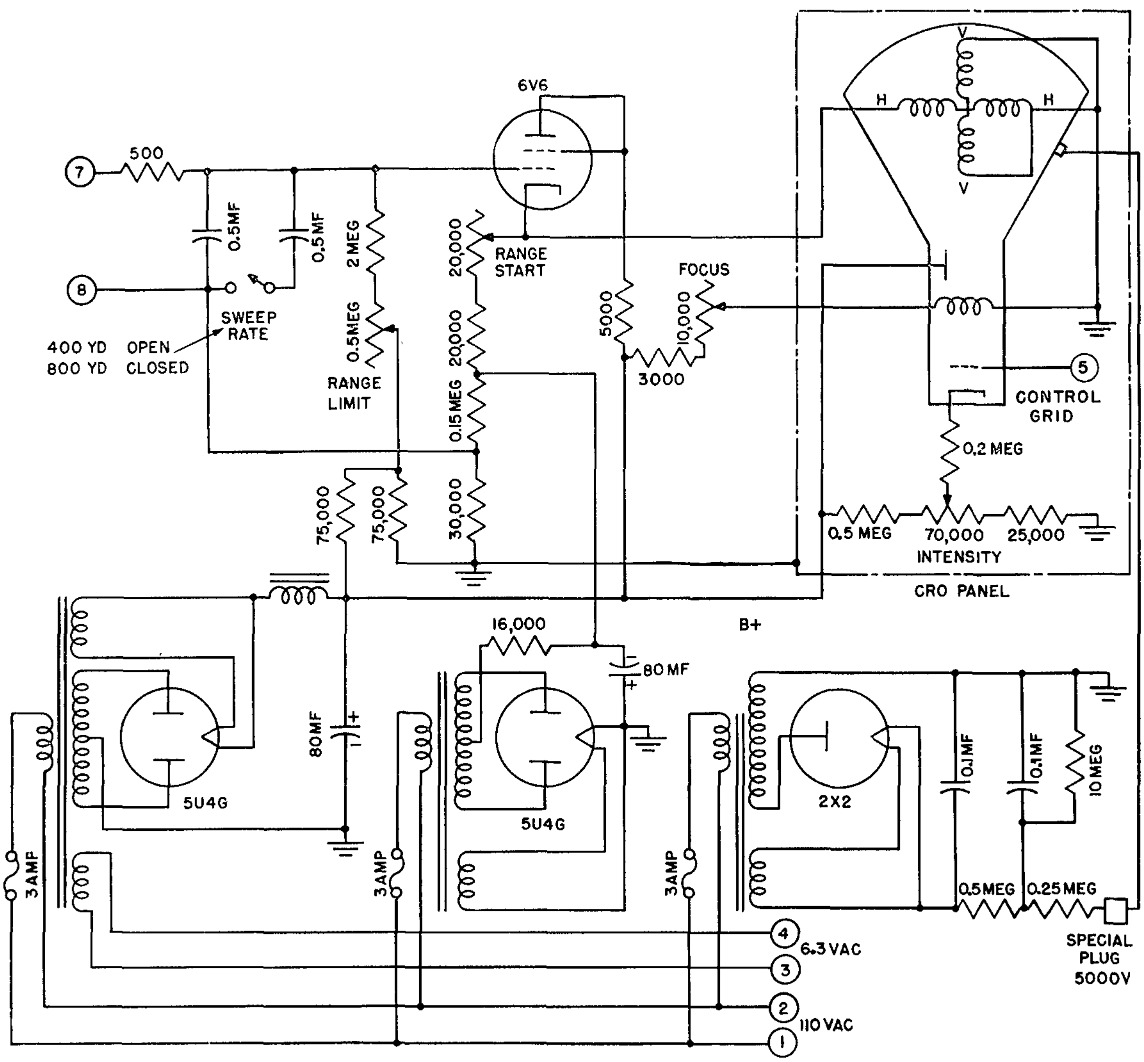


FIGURE 17. Sweep circuit and power supplies, AVS Model II.

possibility of sending sudden surges back through the power supply into the 110-v line.

In the keying arrangement, pulses are initiated by the mechanical timer but are terminated electronically, the timer contacts opening after the pulse is terminated. Ping lengths of 2, 8, and 16 msec are available.

Sweep Circuit and Power Supply. The cathode-ray sweep circuit and power supply are shown in Figure 17. The sweep circuit is of conventional design providing a uniformly changing current to the deflection coils, starting from zero at each ping. Suitable potentiometer controls are available for assuring that the cathode-ray beam starts at the center of the screen and ends at the periphery.

Receiver. The final circuit of the receiver-amplifier is shown in Figure 18. Two of the features of this circuit, *reverberation-controlled gain* [RCG] (see Section 2.5) and doppler sensitization (see Section 4.1), were incorporated after field tests of Model II had been made. A disabling switch on the RCG made it possible to use TVG (see Section 2.2) as originally built into the receiver in place of RCG.

No send-receive relay is used. Rather, to protect the receiver against transmitter voltage, the input is applied to a series-tuned resonant

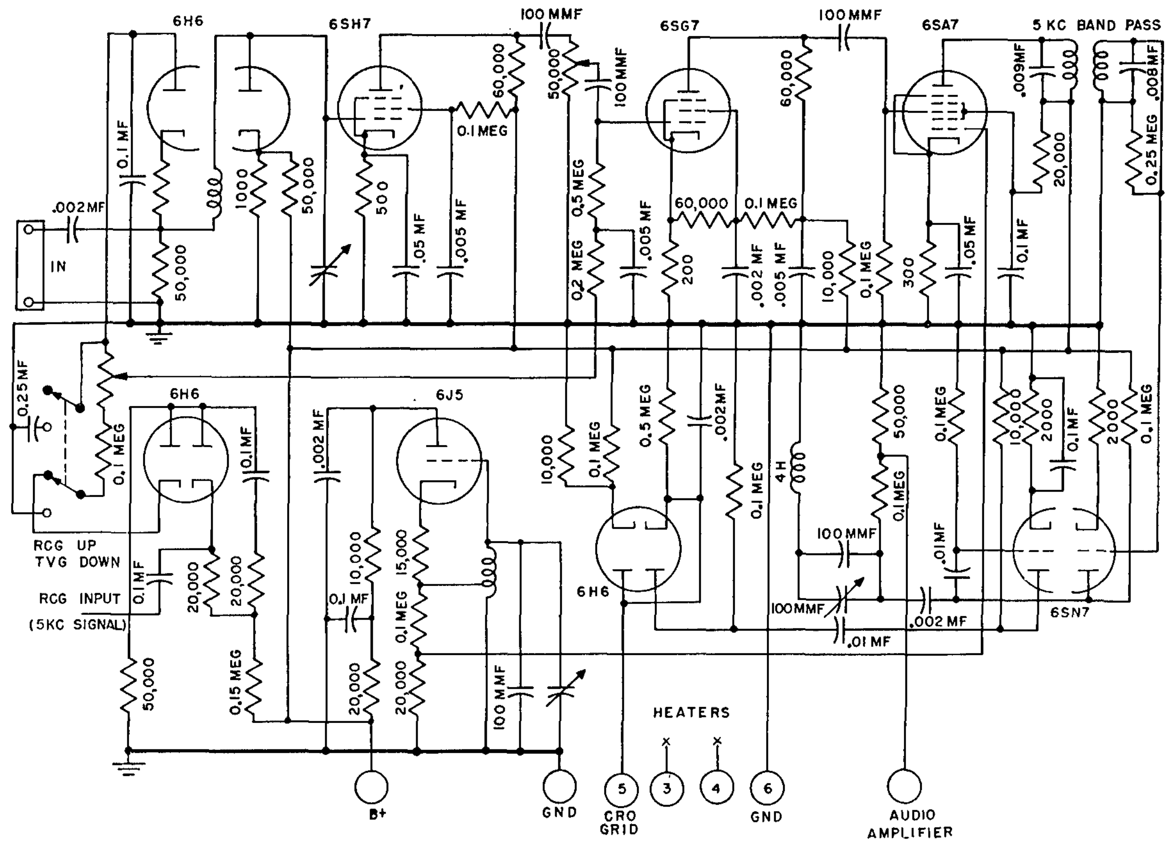


FIGURE 18. Receiver-amplifier circuit, AVS Model II.

circuit which has a diode limiter across the tuning condenser. Half of the 6H6 double diode is used as the limiter and the other half supplies a rectified portion of the transmitter voltage as negative bias for TVG.

Two stages of amplification at signal frequency are employed. The output is applied to a converter tube together with the signal from a local oscillator, so as to produce a 5-kc audio signal. This signal passes through a 5-kc filter with a band-pass of 1 kc, and an additional stage of voltage amplification. It is then applied to the audio amplifier for the loudspeaker and to the voltage amplifier for the CRO brightening. The brightening output is rectified by half of a 6H6 double diode, the second half of which is connected as a limiter to prevent application of more than about 25 v to the brightening grid of a type 5-FP7 cathode-ray tube.

As shown in the diagram, a series-tuned resonant circuit is connected across the plate load of the first audio stage. This is sharply tuned to the audio frequency to enhance echoes with a doppler shift in comparison with reverberation or no-doppler echoes. Since this equipment was contemplated for use on anchored vessels, no difficulties attributable to own-doppler were involved except for possible effects of currents or tides.

As stated above, a portion of the transmitted voltage is applied to a diode rectifier to provide biasing voltage for TVG action. The rectified current is used to charge a condenser whose rate of discharge through a resistance determines the rate of recovery of the amplifier gain. A potentiometer is used in the rectifier output circuit in order to permit adjustment of the initial drop in gain. The rate of recovery is fixed.

Audio Listening System

A separate listening receiver is incorporated for use in the identification of moving objects

producing noise of sufficient intensity to provide a clue to their character. A frequency range from 35 to 45 kc is provided, these frequencies being heterodyned down to audible frequencies in the range from 0 to 10 kc. The receiver chassis does not appear in the photographs (Figures 12 and 14) but was added in the space directly above the transmitter chassis after the photographs were taken. The loudspeaker used for echo ranging may be switched to the listening receiver as occasion demands.

7.6.3 Performance Tests

Sea tests of Model II were made on two different occasions. The first test was made before the unit had assumed its final form. Bathythermograph data showed temperature gradients unfavorable for echo ranging. However, the 3-ft target sphere at 125 yd and its towing vessel at 200 yd appeared in their proper relative locations on the CRO screen. Echoes appeared on four out of five traversals.

Model II was in its final form for the second test. Similar unfavorable echo-ranging conditions were encountered. The 3-ft sphere was detected at ranges from 50 yd to a little over 100 yd, but never at 125 yd or more.

Ping lengths of 2, 8, and 16 msec were tried. It was found that target definition on the CRO screen was much better for the 2-msec ping than for pings of greater length.

Certain adverse test conditions which had a detrimental effect on the performance of AVS may be summarized as follows:

1. The shallow depth at which the projector operated caused the beam to be practically tangent to the surface and therefore considerably affected by waves and by temperature gradients.
2. The small size of the vessel from which the equipment was tested (50-ft motor launch) resulted in erratic motion of the transducer beam. These conditions could have been improved without difficulty if the urgency of the development had been sufficiently great. At the time of the last test, however, the importance of the work had declined and so tests were terminated.

7.6.4 Recommendations

1. Because the ear is at a disadvantage in responding to the short pulses required for the detection of small objects, it is recommended that a recorder be incorporated in the equipment as a supplement to CRO. It has been shown that the memory feature of a recorder is of considerable advantage, particularly when ping-to-ping variations in the received signal are large.
2. Provisions should be made for convenient zero adjustment of the deflection coil and bearing points.
3. If provision is to be made for listening, a listening receiver suitable for frequencies in the audible range should be included in preference to a unit working in the high supersonic range.
4. Test ship facilities more nearly comparable with eventual installation conditions should be made available. In particular, a more stable platform than that of the 50-ft test launch used is regarded as essential for successful operation of AVS equipment employing a narrow sound beam.
5. Deeper submergence of the projector should improve the performance of the system.
6. The simplicity of operation, and clarity of indication sought in this semiautomatic echo-ranging system might prove desirable for purposes other than the one for which it was originally designed. Among such purposes may be mentioned (1) torpedo detection by hydrophone effect, (2) navigation of mine fields, (3) detection of stray mines for harbor clearance, and (4) shallow water navigation. This last-mentioned application might be accomplished by mounting the transducer so that the sound beam is depressed at an angle of 45 degrees to yield bottom reflections at some distance ahead of the ship.

Chapter 8

SMALL OBJECT DETECTION

8.1 INTRODUCTION

Conventional echo-ranging gear used by the U. S. Navy during World War II to detect submarines was designed primarily to detect large objects. It is not suitable for use with small objects such as midget submarines, mine cases, and landing obstacles. When the course of the war made it advisable to provide this additional function, both British and American laboratories undertook theoretical and experimental investigations to determine the design factors characterizing a high performance small object system.

It was soon demonstrated that a most important operating characteristic differentiating small object systems from conventional systems was that of pulse length, and it was believed that for maximum echo-to-reverberation ratio the length of the pulse train in the water should generally approximate the dimensions of the target. Thus a 3-ft target would correspond to a pulse length of 0.6 msec.

On the basis of this principle, the British laboratory at Fairlie developed the 135 Asdic system designed to serve as a harbor protection unit capable of detecting small one- or two-man submarines. This unit proved so successful in detecting mines, pilings, and small-dimension targets that it was quickly adapted to a landing craft-mounted model, the 150 Asdic, and its principles were borrowed to adapt other units, such as the submarine-installed 129 Asdic, to this function.

The several NDRC laboratories, having less urgency assigned to the problem, were somewhat slower in this field of development. Through the courtesy of the British, one of the first of the Asdic units and later a staff member of the Fairlie establishment, were sent to this country to assist our program. As a result of this cooperation and of the experience gained by American research men visiting the British laboratory, two programs were initiated. The first of these was concerned with the modification of existing sonar gear to permit submarines to locate mines accurately and thus enable the safe navigation of the vessel through mine fields. The second, a longer term program, was devoted to a fundamental determination of the physical factors affecting the performance of small object systems, an evaluation of existing systems, and the development of a more ideal system embodying the fundamental principles discovered.

Three developments resulted directly from this program.

1. It was found possible, by a rather simple modification, to adapt the WCA-2 submarine sonar equipment to this function. These modifications are described in some detail in Section 8.4.
2. Two experimental pulsing systems operating at 24 and 90 kc respectively were constructed and tested. These are described in Sections 8.8 and 8.10.
3. An ultra-high-frequency, hand-held system, underwater sound direction and ranging, which operates at very short ranges is described in Section 8.11.

In addition to these systems, it should be noted that both the QH and QL type systems[a] have successfully demonstrated their ability to resolve typical small targets.

8.1.1 Design Considerations

The design of equipment for small object detection is governed by several factors relating to frequency of transmission, pulse length and modulation, and method of indication. Although the physics of echo formation with small, variously shaped targets is not clearly understood, individual laboratories have been able to draw certain empirical conclusions which are reflected in the local choice of equipment parameters. It is probably fair to state that the effects of pulse length and modulation on the expected performance are the most fundamental and the least clearly understood, although a very con-

[a] QH and QL type systems described in Division 6, Volumes 16 and 17, respectively.

siderable amount of work has been done in this field.[b]

Pulse Length

If it is assumed that sufficient power is initially transmitted to make reverberation rather than water noise the limiting factor in echo detection in typical shallow water conditions, then system performance is dependent upon the echo-reverberation (E/R) ratio. The effect of pulse length on reverberation level may be visualized by considering the situation at some particular instant during reception of reflected energy by an echo-ranging transducer. Assume, for convenience, that the acoustical energy sent out by the transducer is contained within the shaded area of the conical beam shown in Figure 1. Energy is reflected back toward the transducer from each elementary particle or surface within the volume thus defined. Energy

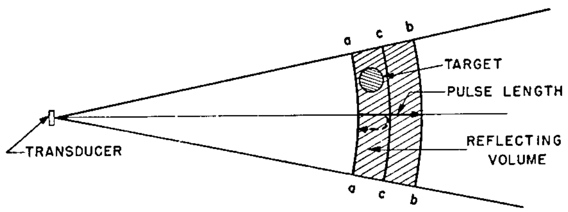


FIGURE 1. Relation between pulse length and reverberation.

identified with the trailing edge is, at the instant shown, starting its return journey from the spherical boundary surface *a-a*. Energy originally associated with the leading edge of the pulse which was reflected backwards when that edge was in the position *c-c* is simultaneously crossing surface *a-a*. Therefore, at the instant in question, energy from all parts of the volume within the spherical boundaries *a-a* and *c-c* is crossing surface *a-a* on the return path. Thus, at each instant throughout the duration of the reverberation, the energy received by the transducer is the summation of all the backwards reflections from a volume contained between

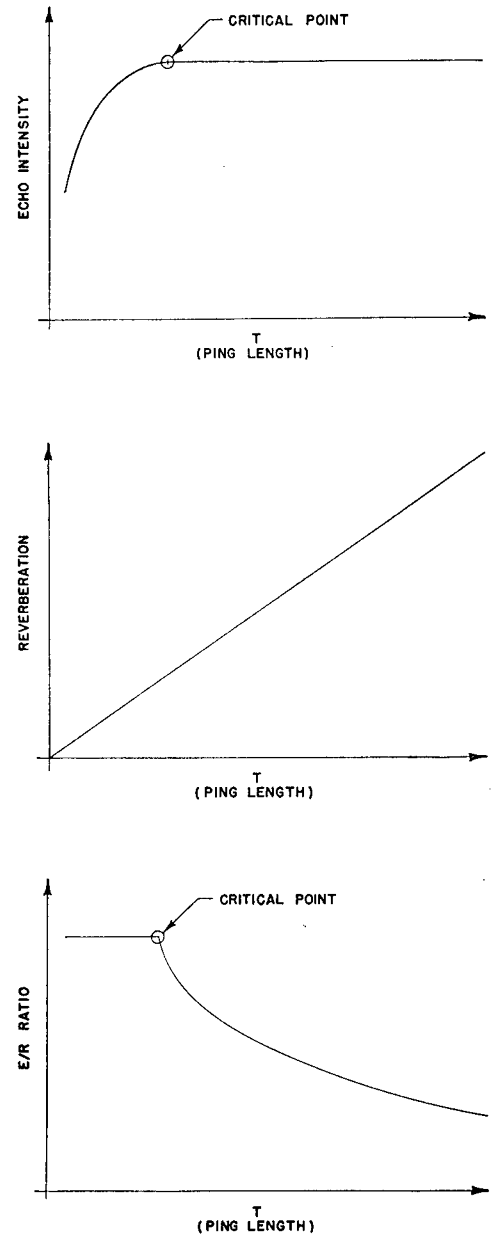


FIGURE 2. Idealized echo and reverberation curves as a function of ping length.

spherical boundaries separated by one-half the length of the pulse. The average level of reverberation can be reduced by shortening the length of the pulse. This has been verfied experimentally.

There is also some reason to believe that for typical targets the average echo level remains constant with decreasing pulse length until a certain critical value is reached. Although this

[b] Since this material is not within the scope of this volume, reference must be made to Division 6, Volumes 7 and 8 and to nonmicrofilmed reports and records of the Naval Electronics Laboratory (formerly UCDWR) at San Diego, California.

value is not known precisely, it is believed to be of the order of the target's dimension. Thus the length of the pulse train in water should approximate the virtual size of the target. This relationship is obviously affected by target geometry. Figure 2, which presents idealized curves for echo and reverberation levels as a function of pulse length, indicates a critical pulse length for maximum E/R ratio.

The benefits of high E/R ratio can also be obtained with a frequency-modulated transmission as employed by the QLA sonar. In this case, the method of heterodyning echo frequency with transmission frequency limits the reception of signals to an annular region whose width is essentially determined by the width of the receiver acceptance band for the heterodyned frequencies. The use of continuous f-m signals or of f-m pulses or "chirps" also provides a method of minimizing standing wave interference which often proves troublesome with single frequency transmission in shallow water. In short pulse transmissions, the attendant sideband components serve the same purpose.

Preliminary investigations have indicated that better ratios might be obtained for particular target shapes by the use of tailored pulse-envelope shapes. The results of these experiments, although incomplete at this time, show some promise for future specialized systems designed to detect one or more special types of targets.

Transmission Frequency

Several considerations apply in choosing the transmission frequency. The lower frequencies permit longer ranges but require larger transducer dimensions for fixed beamwidth and increase the difficulty of shaping the pulse modulation envelope. Higher frequencies, although easier to handle, tend to decrease the maximum possible range. An engineering compromise must be determined on the basis of the proposed tactical application and permissible transducer size.

Electrical Characteristics

The sensitivity and selectivity of the transducer and the associated transmitter and receiver circuits are primarily determined by the pulse length and modulation and the transducer beam pattern. While reverberation-limited operation generally makes the use of high transmission power unprofitable, under some conditions of low reverberation the use of very high peak powers may be justified.[c]

Methods of Indication

The long memory feature available with chemical paper recorders has been found helpful in establishing the presence of low level targets. This is particularly true when characteristic patterns, such as mine fields, can be identified. Good results have been obtained by modifying standard recorders to present a more continuous and sharper pattern in both time and range scales.

Existing recorders do not permit a true *plan position indicator* [PPI] presentation. For this reason and because of a more favorable and easily adjusted sensitivity differential, the use of *cathode-ray oscilloscope* [CRO] tube indicators is proposed. At the present time, the choice of indicator is determined by the application. Future systems, however, will probably incorporate both methods, as has XQHA sonar, in order to secure the full advantage of high resolution, PPI display, and long memory.

[c] In this connection recent work in high-power short pulse transmissions, described in Division 6, Volume 13, may be of interest.

Mine and Torpedo Detection Equipment

Mine and torpedo detection equipment [MATD] is supplementary equipment, designed for use with WCA-2 gear, to provide a plot of a mine field on a cathode-ray tube. To modify the WCA-2 equipment for mine detection, electronic circuits were added to provide a short pulse, amplitude modulation of the pulse, and CRO indication. The original function of the WCA-2 equipment is not impaired by the MATD modification. Provision is also made in the MATD unit for torpedo detection. Development of the mine and torpedo detection equipment was carried on by Columbia University, Division of War Research, Underwater Sound Laboratory, New London, Connecticut.

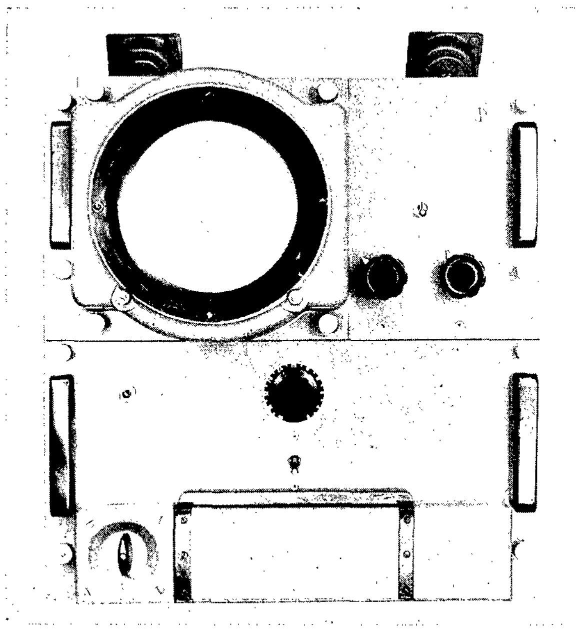


FIGURE 3. MATD unit in cabinet.

8.2 INTRODUCTION

Late in 1944, information from the Commander of Submarines, Pacific Fleet, indicated urgent need for mine detection equipment. Investigations in the general problem of submarine echo ranging indicated that existing echo-ranging equipment could be adapted to this service with only minor modifications.

Principal modifications included a 5-msec pulse, amplitude modulation of the pulse, and CRO indication. Provision was also made for torpedo detection by hydrophone listening. All original systems components were retained without loss of original function.

Preliminary tests of the prototype model confirmed the suitability of the modified system. As a consequence, 12 sets of MATD were under construction for use in training at the time the project was taken over by the Naval Research Laboratory and an additional number were on order from the Submarine Signal Company.

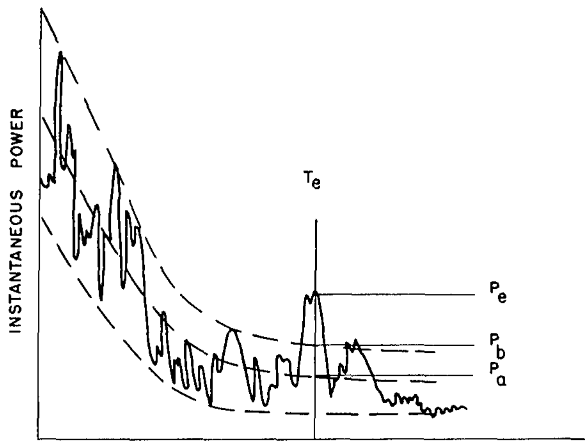
8.3 THEORETICAL CONSIDERATIONS

The ability to detect the presence of a target by echo-ranging methods is generally limited by reverberation. Immediately following the transmission of a pulse of supersonic sound, a burst of energy returns to the transducer, continuing at a decreasing rate, for some time thereafter. Observations of the level of intensity as a function of time show many sudden and unpredictable irregularities in energy received. These result from the various random discontinuities encountered by the outgoing pulse. Energy reflected from a target is not inherently different in character from that returned by any other reflecting agent. It can, therefore, be identified only if it constitutes a significant irregularity in the time-intensity pattern of the returned radiation.

The curve of Figure 4, traced from an actual oscillogram, shows the random nature of reverberation. Assume that at time T_e an echo appears at the terminals of the transducer. In order that this echo be detected, it is clear that any increase it causes in the general reverberation pattern must be significantly greater than the random variations due to other causes.

TRANSMITTED PULSE

Pulse Length. The average level of reverberation could be reduced by shortening the length of the pulse. Decreasing the length of a long pulse would have no effect on the level of an echo from a mine; it would merely affect the duration of the signal. If the pulse length is



P_a = AVERAGE LEVEL OF REVERBERATION
$P_b - P_a$ = POSSIBLE RANDOM DEVIATION
$P_e - P_a$ = MINIMUM DETECTABLE INCREMENTAL SIGNAL

FIGURE 4. Representative reverberation pattern.

too short, however, the intensity of the reflected signal suffers. An optimum pulse length is therefore somewhat near this minimum figure, and thus depends on the size of the target under search.

Amplitude Modulation. A more general study of echo ranging which preceded the work on mine detection included an investigation of the effect of modulating the amplitude of the transmitted pulse. The reflected signal was found to stand out more clearly against a background of reverberation when the pulse was modulated.

Multiple transmission paths between an echo-ranging transducer and the succession of reflecting surfaces encountered by the pulse distort the relation between the time variation of reflectivity and the time variation of received signal. In steady state transmissions these multiple paths result in the appearance of standing waves. These are known to be less prominent when the transmitted wave is made up of a number of components covering an extended band of frequency than when a single frequency is used. A complex wave of short duration should produce a more reliable picture of changes in reflectivity than a single frequency wave of the same duration. A short pulse, nominally at a single frequency, actually contains high-frequency components as a result of the transients accompanying initiation and termination of the pulse. There is some evidence to show that the clarity of the reverberation picture obtained with short pulses results in part from the presence of these transient components. The number and amplitude of these components may be altered by changing the envelope of the transmitted pulse while maintaining essentially a constant duration.

THE CRO

Certain characteristics of the CRO make it suitable as the indicator for mine detection equipment. By using PPI type of presentation, with a CRO, the bearing, range, and relative position of any target giving a distinguishable echo signal may be read at once from the position of the trace on the screen.

Persistent screens are helpful in establishing the validity of any echo signal suggestive of the presence of a mine. When using the CRO for PPI presentation, any bearing showing a questionable echo pattern may be reexamined. The trace of the new pattern will fall on or near the previous traces and aid in ascertaining more definitely the presence or absence of a target.

COMPENSATION FOR RANGE LOSS

It is highly desirable to vary the gain of the receiver-amplifier with time to compensate for decreasing signal strength with range.

A control, similar to the *time-varied gain* [TVG] (see Section 2.2), is applied here. It is called *compensation for range loss* [CRL] to emphasize the fact that it is adjusted to fit a predetermined relation between range and loss. The variation in gain selected provides for an increase in gain at the rate of 12 db per distance doubled, a rate which is consistent with a signal level which decreases as the inverse fourth power of the time.

SEARCH RANGE

The determination of range is largely a matter of judgment. It is unwise to carry the

search operation to maximum possible ranges. In the first place there are no reliable statistical data to provide a relation between range and the probability of detection. It is thus impossible to select a range as representing the boundary between assured and questionable detection.

Figure 5 shows the geometry involved in searching a path of given width centered on

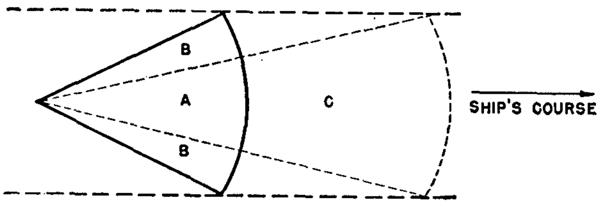


FIGURE 5. Relation between operating range and reliability of detection when searching a given path.

the submarine's course. The length of the search range and the breadth of the path scanned immediately fix the angle of the sector which must be searched. The directivity pattern of the projector determines the number of echo transmissions required to search this area adequately. Inasmuch as the range fixes the duration of each echo transmission the total time for one complete scanning operation is

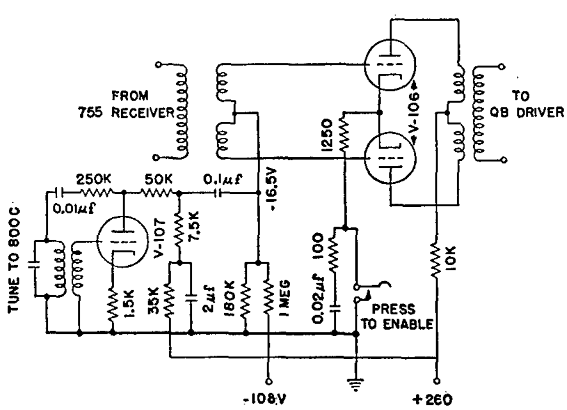


FIGURE 6. Circuit for producing amplitude-modulated pulses.

completely established. Assume now that the equipment is modified so that it searches to twice the former range. If the same path width is to be surveyed, it is apparent that the angle to be scanned is reduced to approximately half its former value. One-half as many echo transmissions will be required, but the time for each will be twice as great. The total time required to scan the new sector is thus the same as in the first place although the area is twice as great. The fact that a greater area is covered is by no means as advantageous as might at first appear. It is true that there is a somewhat questionable possibility of earlier detection. There is, on the other hand, no question about the price which this entails; the path formerly swept with some definite, although unspecified, degree of reliability is cut in half, its width and the reliability with which the remainder is cleared is greatly impaired.

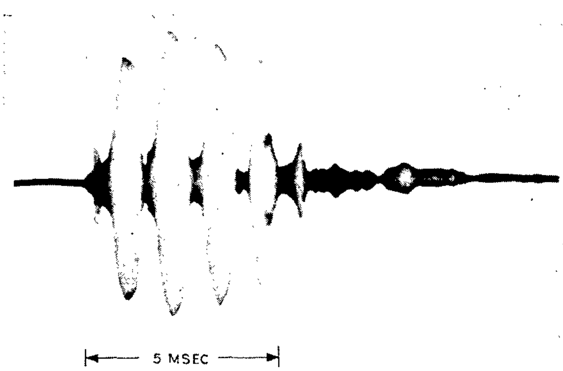


FIGURE 7. Oscillogram of amplitude-modulated supersonic pulse in water.

In selecting a value for the range to which the search operation is to be carried it is necessary to make intuitive compromises between the reliability of detection and the time available for avoiding action. The combined judgment of a number of people having experience with this problem has resulted in the adoption of a range of 600 yd as a reasonable value. During operational trials of the equipment, no convincing evidence has appeared to indicate that this somewhat arbitrary choice is in obvious need of revision until greater submerged speeds are at hand.

8.4 WCA-2 GEAR MODIFICATION

A dominant factor controlling this new laboratory equipment was the necessity for utiliz-

ing existing WCA-2 equipment. It was also necessary to plan the system so that the WCA-2 gear would be instantly available for its normal echo-ranging service.

Transmitting Circuit

The major change required in the transmitter was the addition of circuits for the amplitude modulation of the outgoing pulse. The supersonic wave normally transmitted by the WCA-2 system is derived as a product of modulation between a wave of adjustable frequency (73 to 97 kc) generated in the first oscillator of the receiver-amplifier and a wave of fixed frequency (60 kc) generated by a stable oscillator in the QB driver. The frequency of the outgoing wave corresponds to the difference between these two frequencies, and, except for doppler shifts, the returned echo signal has this same frequency. In the receiver this signal is heterodyned against the same frequency generated by the first oscillator of the receiver and hence yields a signal, one component of which has a frequency the same as that of the stable oscillator (60 kc). This arrangement insures that the output of the modulator of the receiver-amplifier is of the correct frequency to be accepted by the intermediate frequency stages regardless of the frequency to which the first oscillator is adjusted, and hence regardless of the frequency of the transmitted wave.

With this arrangement it is possible to modulate the outgoing pulse by introducing a modulating circuit between the first oscillator of the heterodyne receiver and the supersonic modulator of the QB driver. The details of this circuit are shown in Figure 6. The high-frequency wave from the first oscillator of the receiver-amplifier is modulated in tube V-106 by the 800-c output of the local oscillator circuit including tube V-107. After subsequent modulation in the QB driver by the fixed 60-kc wave, a supersonic carrier wave with 800-c sidebands is thus obtained.

The special key in the cathode circuit of tube V-106 serves as an electronic switch to control the duration of the pulse. The cathode circuit is left open except for the short interval during which the pulse is desired. With such a switch the main keying relay is called upon to perform merely a transfer function and

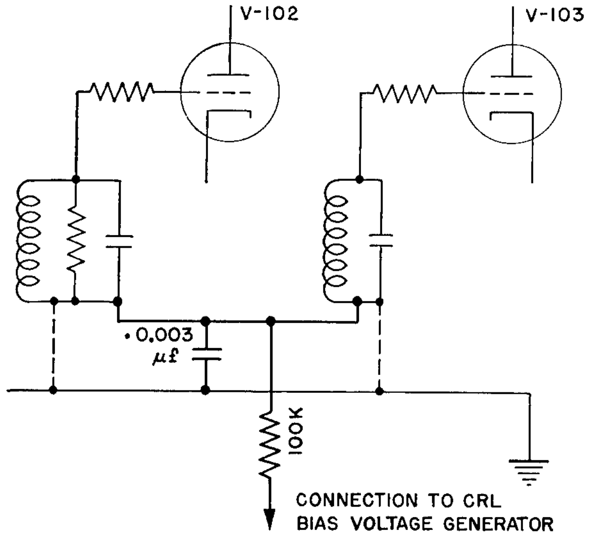


FIGURE 8. Modification required in wiring of 755 receiver-amplifier to adapt it to CRL control.

is not required to break a circuit carrying the full output current of the driver amplifier.

Figure 7 shows an oscillogram of the resulting modulated supersonic pulse put into water by a QB transducer and picked up by a monitoring hydrophone.

Receiving Circuits

The only modifications required in the receiving circuits are those necessary to provide compensation for range loss [CRL]. This was

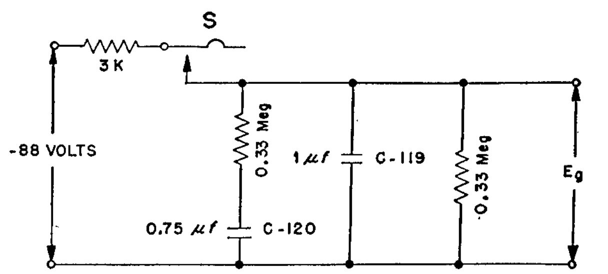


FIGURE 9. Generator for CRL bias voltage.

accomplished by applying an appropriately varying bias to the first two stages of the i-f amplifier. Figure 8 shows the changes in the

wiring of the 755 receiver-amplifier to introduce this bias.

The circuit, shown in Figure 9, is an elaboration of a simple condenser discharge circuit. Condenser C-119 is charged during the 20-msec recovery period that switch S is closed. Condenser C-120, however, does not become fully charged during this short interval. It therefore draws charge from C-119 during the first portion of the operating interval; during the remainder of the interval it supplies charge to C-119. Consequently, the output voltage, E_g, decreases more rapidly during the first portion and less rapidly during the latter portion of the operating interval than it would if a simple RC circuit were employed, and thereby approximates the desired voltage-time characteristic.

THE PLAN POSITION INDICATOR

CRO Bearing Repeater. The distinguishing feature of the CRO system is the use of a very

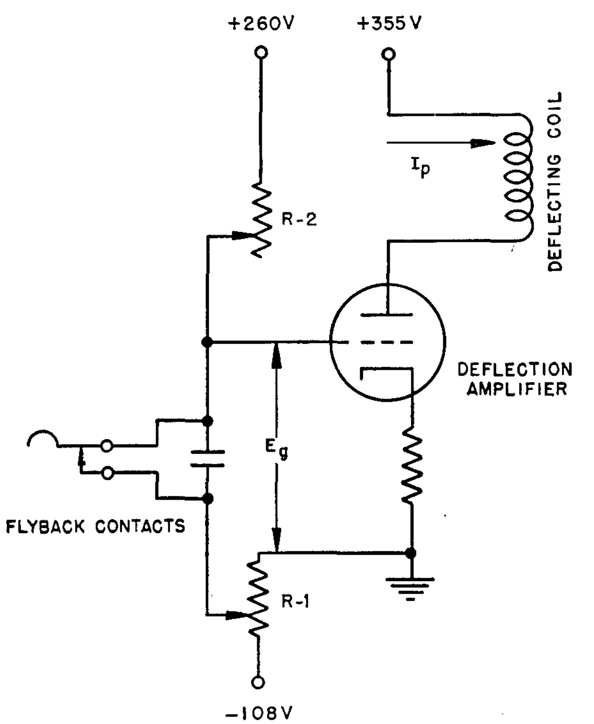


FIGURE 10. CRO sweep deflection circuit.

light deflection coil carried on ball bearings which makes it possible to drive the deflecting coil mechanically by means of a selsyn motor connected through a 10/1 gear ratio. A special relay system is provided to guarantee proper indexing between the orientation of the CRO deflection coil and the orientation of the projector.

CRO Deflection System. A radial sweep is provided in this MATD system by passing a sawtooth current through the CRO deflection coil as the latter rotates in synchronism with the projector.

Current for the deflection coil is provided by the beam power amplifier tube of Figure 10. A sawtooth voltage is impressed on the grid of this tube by means of a conventional condenser charging circuit. The setting of R-1 determines the bias voltage applied to the grid when the condenser is short-circuited. The setting of R-2 determines the rate at which the condenser charges when the short-circuiting key is opened, and hence determines the rate of sweep. For a full-scale range of 600 yd the zero position of the spot is displaced approximately 20 yd. A small circle drawn on the face of the cathode-ray tube facilitates adjusting R-1 to its appropriate value.

CRO Brightening System. Control of the intensity of the CRO electron beam is effected by the brightening circuit of Figure 11. The setting of potentiometer R-1 determines the

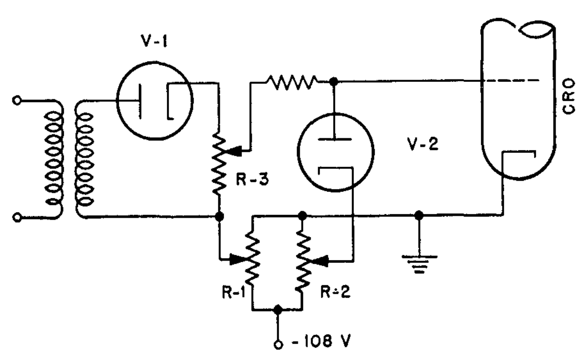


FIGURE 11. CRO brightening circuit.

negative bias applied to the grid at zero signal. When an alternating current signal from the receiver-amplifier is rectified by V-1, a d-c drop appears across R-3. This decreases the negative potential applied to the control grid and thus intensifies the CRO beam.

Diode V-2 is introduced to limit the d-c voltage that can be applied to the CRO control grid

to avoid damaging the screen as a result of intense signals. The setting of potentiometer R-2 determines the value of this limiting voltage.

Cycling Switch

A simple and reliable mechanical control was selected which utilizes a series of contacts operated by cams driven by a synchronous motor. The range of 600 yd fixes the operating interval at 750 msec. By driving the camshaft at 78 rpm the complete cycle is repeated every 770 msec, leaving a recovery interval of 20 msec before each transmission.

The diagram of Figure 12 illustrates the sequence of events associated with each cycle. At the expiration of each 750-msec scanning

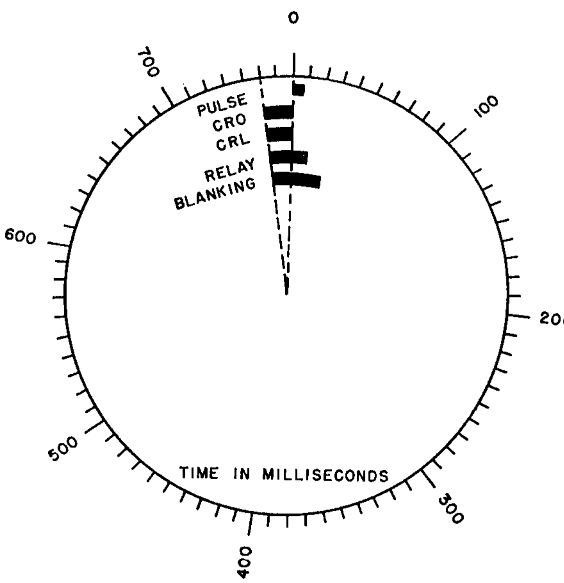


FIGURE 12. Cycle of MATD operation.

interval, four individual cams effect four simultaneous switching operations: (1) the condenser of the sawtooth generator controlling the oscilloscope sweep is short-circuited, thus returning the cathode-ray spot to its starting position; (2) the oscilloscope screen is blanked by removing the ground connection to its cathode (to avoid a return trace); (3) the charging contact of the network supplying the variable CRL voltage to the 755 receiver-amplifier is closed; (4) the transfer relay connects the transducer to the driver-amplifier in readiness for the next transmission.

At the termination of the 20-msec recovery period a fifth cam enables the electronic switch (see Figure 6) which initiates transmission of the pulse. These contacts remain closed for 5 msec. Shortly after transmission of the 5-msec pulse, the transfer relay restores the system to the receiving condition, and a final operation terminates oscilloscope blanking. This last event is delayed for a time equivalent to a 50-yd range to prevent excessive illumination of the screen due to intense local reverberation.

Some difficulty was experienced in devising a cam-and-contact combination which would permit close adjustment and maintenance of an interval as short as 5 msec. However, by using a type of contact in which both the make and the break occur as the result of the sudden release of a contact spring from an undercut face of the cam it was found that intervals of even shorter duration could be defined with adequate accuracy.

Modifications for Torpedo Detection

The system described in the preceding paragraphs contains the elements essential for torpedo detection as well as for mine detection. It is possible to "listen" continuously for approaching torpedoes, with transducer rotating, and present the information received on the CRO screen as a function of bearing. The intensity of the signal can of course be made to determine the radial position of the CRO spot.

When the equipment is employed for torpedo detection the received signal is used to supply the grid voltage for the oscilloscope deflection amplifier in place of the sawtooth generator component of Figure 10. A logarithmic amplifier[1] is inserted between the output of the 755 receiver-amplifier and the input of the oscilloscope deflection amplifier. This arrangement provides approximately equal changes in deflection for equal percentage changes in level of the received signal over a fairly wide range of signal level. The fixed bias of the deflection amplifier is adjusted so that the deflection current holds the CRO spot at the outer edge of the screen when no signal is superimposed. Thus,

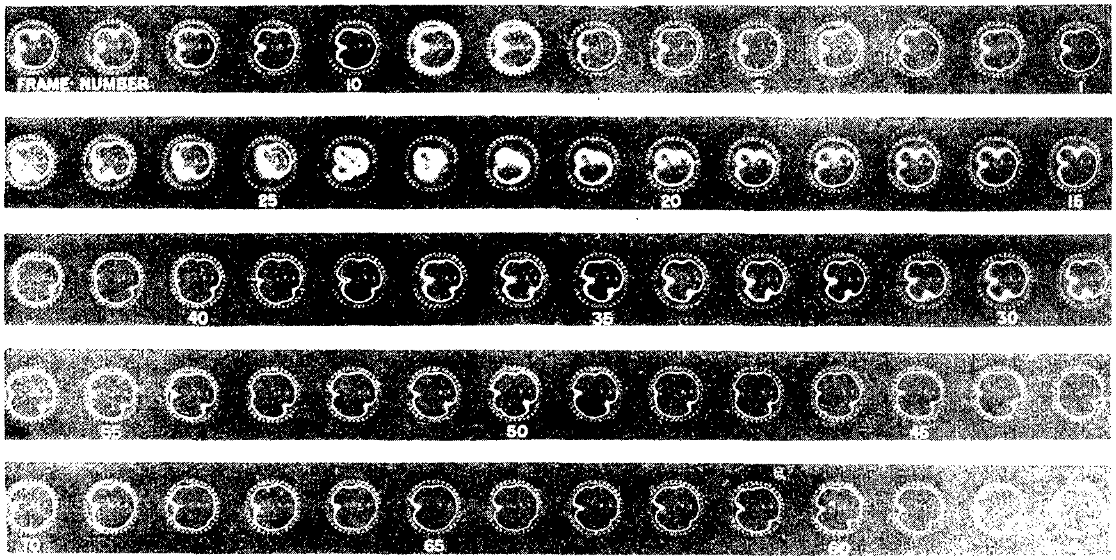


FIGURE 13. Consecutive oscillographs of torpedo passes.

as the transducer rotates, the spot traces a circle the diameter of which is nearly equal to the diameter of the screen. The audio output of the logarithmic amplifier is impressed directly onto the deflection amplifier after having first

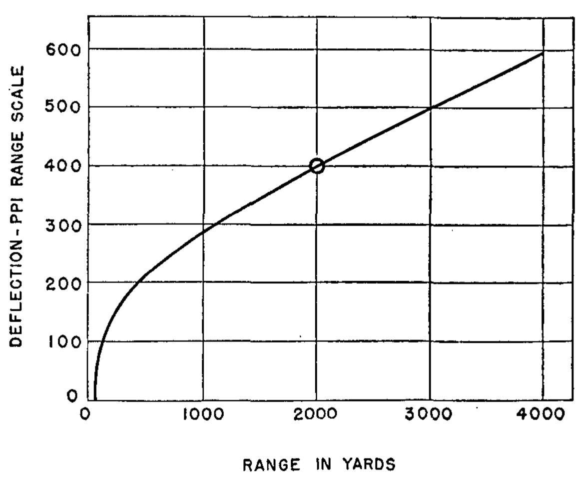


FIGURE 14. Range of detection for representative torpedo.

been rectified. With this system, the spot follows an irregular path with the radial displacement of the CRO spot indicating the level of the sound falling on the transducer. Typical patterns are shown in Figure 13. By assuming some reasonable value for the sound output of a torpedo it becomes possible to predict with moderate assurance the range at which detection may be expected on any bearing. Once a torpedo is detected it is also possible to estimate its range from the deflection of the CRO trace. The relation between range and oscilloscope deflection for a representative torpedo is given in Figure 14.

Mechanical Arrangement. Except for the bearing repeater unit attached to the projector shaft and the circuit elements added to the 755 receiver-amplifier, all the equipment initially associated with the MATD modification is mounted on two chassis and housed in a single cabinet, as shown in Figure 3.

8.5 OPERATING TESTS

MINE DETECTION TESTS

Following laboratory tests, preliminary models were mounted on a relay rack on board a surface ship for testing at sea in conjunction with a WCA-2 system. The majority of this work was carried out in approximately 100 ft of water and over a smooth sand bottom. Actual mine cases were used, and well-defined echoes were obtained on most attempts.

Scanning Rate. During early operating trials attention was given to the determination of a suitable scanning rate. It appeared that when working to a maximum range of 600 yd the transducer might safely be rotated at about 2 to 2½ degrees per operating cycle. Thus, the scanning rate was set at 3 degrees per second.

Appearance of CRO Screen. When operating at sweep speeds of 3 degrees per second, several echo traces usually appear whenever the bearing of a mine case is crossed. Figure 15 shows

FIGURE 15. Appearance of CRO when echo ranging on mine cases.

the appearance of an oscilloscope screen on which are recorded echoes from two separate mine cases which exhibit a recurrence not characteristic of other random markings.

Definite indications appear on the screen as a result of irregularities in the environment. These sometimes appeared as brightened portions of the screen corresponding to areas 100 yd or so in length and 30 or 40 yd in width. On subsequently traversing these areas with a fathometer these markings were found to be associated with fairly abrupt, although slight, changes in depth.

Response to Noise. With a noise source in the direction of the transducer axis, the receiver gain may reach a value such that the spot will become visible and trace a line of ever increasing intensity for the remainder of its transit. It is apparent that the length of this line is a measure of the intensity of the noise. In fact, it is possible to provide the system with a radial scale so that noise level can be measured as a function of bearing.

The response of the system to a noise source is a major factor in determining the level at which acoustical energy must be put into the water by the transducer to be assured of satisfactory echoes. This must be sufficiently high so that the average level of reverberation is above the background noise level throughout the entire operating interval. This condition was found to be satisfied with an input to the QB transducer of approximately 60 watts when test ship was under way at full speed, except for bearings within about 25 degrees either side of ship's-own screws.

Security Tests. A number of tests were made to determine the range at which operation of the mine detection gear might be picked up by the enemy. A WCA-2 installation on a listening vessel was tuned to maximum response while several approach runs were made. The average range of first detection was 4,000 yd. One reason assigned to this short range of detection, which is significantly lower than that commonly experienced in normal echo-ranging operations, is the short pulse length used. As there is no sensation of tone, the pulse is less easily distinguished from incidental water noises than pulse lengths of longer duration.

TORPEDO DETECTION

The sequence of photographs of Figure 13 shows the appearance of the CRO screen as a torpedo passes test ship when the MATD system is switched to torpedo detection. Each exposure corresponds to one complete rotation of the projector shaft, or to a time interval of 5 sec. The indentation appearing at the left of each photograph (at bearing 180 degrees) is due to ship's-own screws. Frame 1 gives warning of the approach of the torpedo at bearing 270 degrees. Nearest approach occurred during the interval recorded in frame 23, 1 minute and 50 sec later. Assuming a

speed of 40 knots for the torpedo, detection was possible at a range of at least 2,500 yd.

Submarine Tests of Prototype Model

When the project under which this equipment was developed was first authorized, it was assumed that its basic purpose was to give warning of the proximity of a mine and to disclose its location with sufficient accuracy to permit avoiding action to be taken. Later it appeared that the gear might be called upon to provide information sufficiently complete and accurate to permit the preparation of chart overlays to show the positions of all mines in a mine field. Its use for this purpose was, therefore, studied in considerable detail during the operational tests aboard a submarine.[2] In general it may be said that once a mine was detected the range and bearing information obtained by means of the MATD unit was of greater accuracy than could be obtained by any method available as a check.

8.6 CONCLUSIONS

Operation at Higher Carrier Frequency

During surface ship trials a few tests were made to determine the effect of operating frequency on performance. By operating at a higher carrier frequency one would expect an improved reverberation-to-echo signal ratio as a result of the more sharply defined transducer beam.[1] In order to verify deductions based on such considerations tests were carried out at 60-kc carrier frequency using the standard QB projector and a specially designed heterodyne receiver in place of the 755 receiver-amplifier. A marked improvement in the ability of the system to detect small changes in signal level was noted. Tests were conducted out to a range of 1,200 yd. On practically every occasion it was possible to obtain well-defined echo signals from a 36-in. mine case.

It should be pointed out, however, that attenuation becomes appreciable when using a 60-kc carrier. This appeared as a significant part of the transmission loss for ranges in excess of 500 or 600 yd.

Variability of Reception

The well-known fact that water conditions have a marked effect on signal strength was observed during both the submarine and the surface ship trials. In a given location and with negligible thermal gradients, echo signals varied from levels which were barely detectable to levels which raised the spot intensity to its maximum value. No assignable cause has yet been discovered which can be rigorously correlated with this variation.

Advantage of Simultaneous Aural and Visual Detection

Experience gained with both the oscilloscope and the chemical recorder in connection with the submarine torpedo detection tests described above show that, regardless of the excellence of any visual indicator, the warning of an approaching torpedo might be advanced if aural as well as visual means were to be used for the observation of received signals.

UCDWR Small Object Detectors

The UCDWR small object detector is a small medium-power echo-ranging system designed to provide detection of mine cases and other small objects at maximum range. It is intended primarily for installation aboard submarines and mine sweepers although its principles may be applied to other installations. The system consists of a 24-kc ADP transducer driven by a 250-watt transmitter. Echoes are received by a three-stage amplifier and indicated on a modified chemical paper recorder. For maximum target resolution, a pulse length variable from 0.1 to 3.0 milliseconds is provided. With this system typical mine fields can be de-

tected and plotted at ranges in excess of 1,000 yards under ideal water conditions. It is believed that overall performance might be improved by the provision of A-scan indication and greater acoustic power. Some experimental work was also done on a 90-kc system. Three experimental models were constructed by the UCDWR, one of which was installed and provided successful operation on a fleet-type submarine.

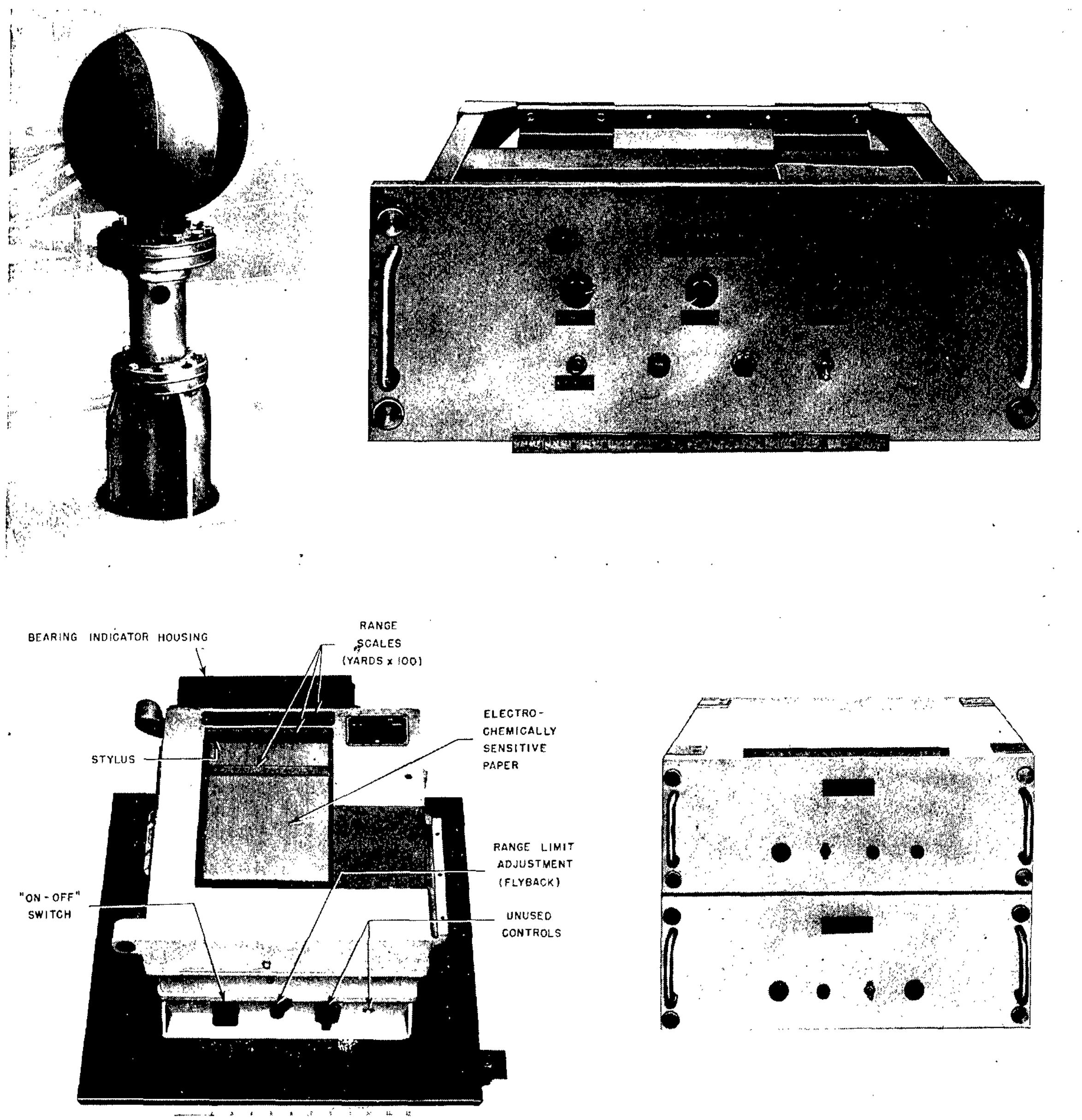


FIGURE 16. (*Upper left*) JB4Z transducer installed aboard submarine. (*Upper right*) Model I (500) SOD receiver (front view). (*Lower left*) Model II 501 SOD chemical recorder and bearing indicator assembly. (*Lower right*) Model I (500) SOD transmitter and relay rack.

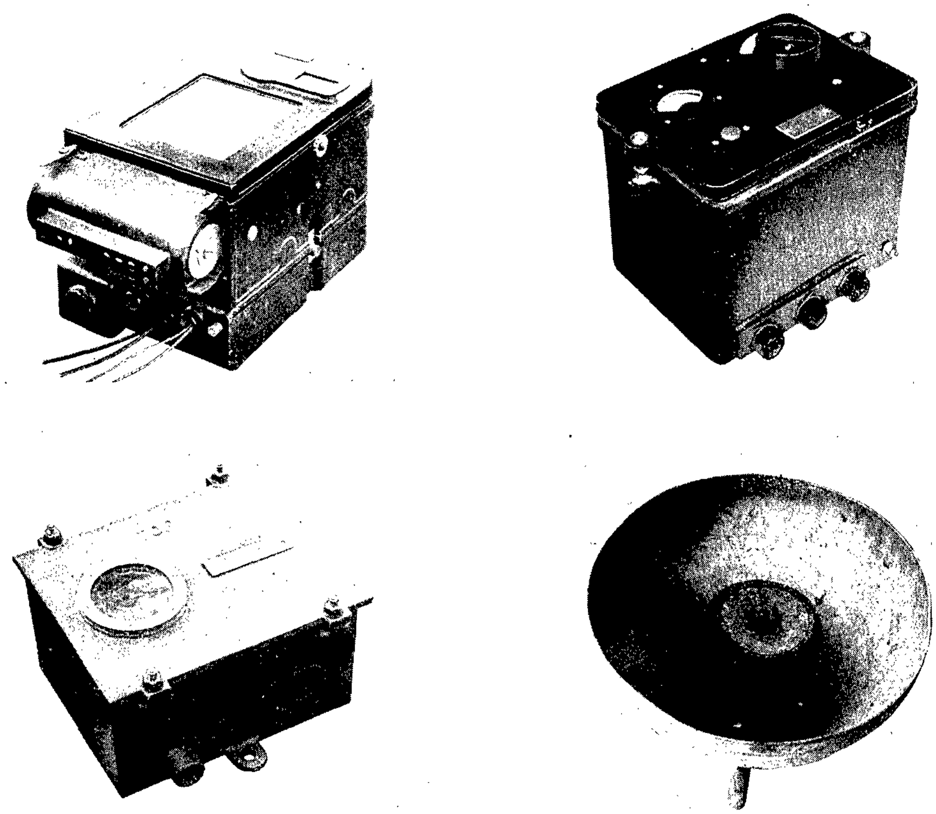


FIGURE 17. British Asdic 135 equipment. (*Upper left*) Chemical recorder, (*upper right*) receiver unit, (*lower left*) transmitter unit, (*lower right*) transducer, showing separate transmitting and receiving elements mounted coaxially.

8.7 INTRODUCTION

In the early part of 1944, UCDWR was authorized to (1) evaluate existing British small object detection equipment, (2) determine the feasibility of modifying standard pinging echo-ranging gear for long-range (1,000-yd) detection of mines and landing obstacles, and (3) develop small object detection equipment to detect small objects effectively at fairly long ranges.

The first SOD devices tested were the British Asdics 135 and 150, designed for location of tagets at ranges up to 600 yd. The Asdic 135 is a pinging echo-ranging device which operates on a frequency of approximately 15 kc and is designed primarily for harbor protection installation. It is composed of four units: transducer, transmitter, receiver, and recorder (see Figure 17). A short transmission pulse, approximately ¼ msec, is produced by shock-exciting the magnetostriction transducer. The received echo is detected by a separate magnetostriction transducer unit. The output of the receiver is applied directly to the stylus of a chemical-type recorder (Figure 18). This figure also shows typical recorder traces as obtained on 3-ft diameter mine cases as targets. An improved receiver output filter (subtraction unit) was later added to this device to increase target to background discrimination on the recorder paper.

The British Asdic 150 is essentially a 135, modified for mobile operation on landing craft.

Although ranges exceeding 1,000 yd on captive mines had been demonstrated at Fairlie with this equipment, maximum ranges of only several hundred yards were reported by the UCDWR laboratory. Although the cause for this discrepancy in performance is not defi-

FIGURE 18. British 135 Asdic recorder traces.

nitely known, it is believed to be the result of faulty transducers and unfavorable conditions of testing.

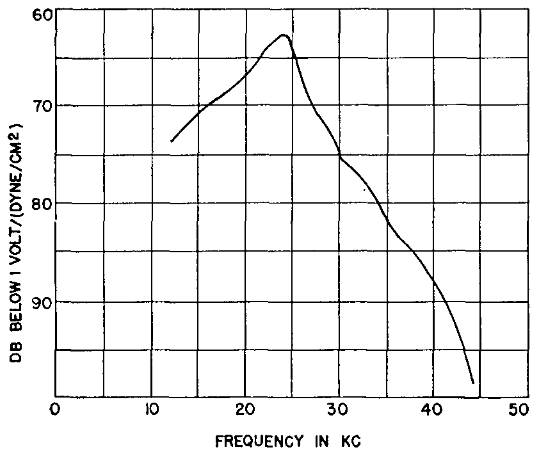
Pinging echo-ranging equipments then in standard use were also evaluated. Tests indicated that they were unsuitable for long-range small object detection because of their relatively long ping periods (50 to 200 msec) which caused extremely low echo-to-reverberation ratios, especially in shallow water. It was believed that extensive modifications would have to be made in such components as the keying circuits, transducers, and receivers, in order to convert them for long-range small object detection.

An evaluation was also made of the Navy panoramic recorder, which provides a permanent plot of positions of obstacles with respect to the course of a survey vessel. Many tests were conducted from a stationary barge but the results were considered unsatisfactory, mainly because of the equipment's insensitive paper. This paper is a special type, "Teledeltos," and it was impossible to substitute more sensitive chemical papers for it. As a result of these tests, no shipboard installation was made for further test.

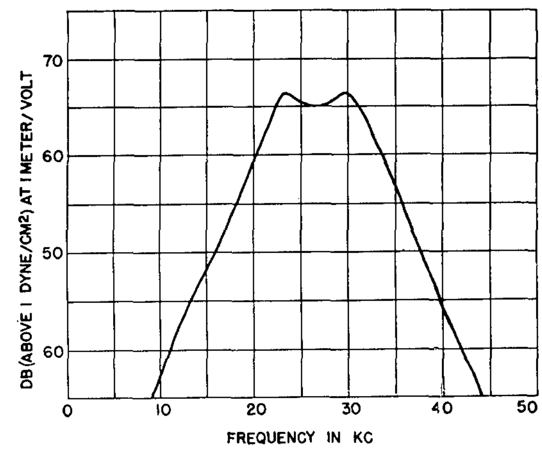
In view of the importance of the application, it was felt worth while to build an apparatus designed specifically for SOD. Because of the desire for higher performance than obtained with the models described, a program was instituted for the development of small object detection devices. Several experimental 24-kc models were constructed to evaluate the proposals for long-range small object detection; a 90-kc device, utilizing another system of pulse keying, was also constructed to investigate very short pulses and the feasibility of higher frequencies.

In New York and later in San Diego, Dr. Willis of the British Laboratory at Fairlie, who had been instrumental in the development of the British Asdics 135 and 150, made a number of constructive suggestions regarding future further development of SOD devices.

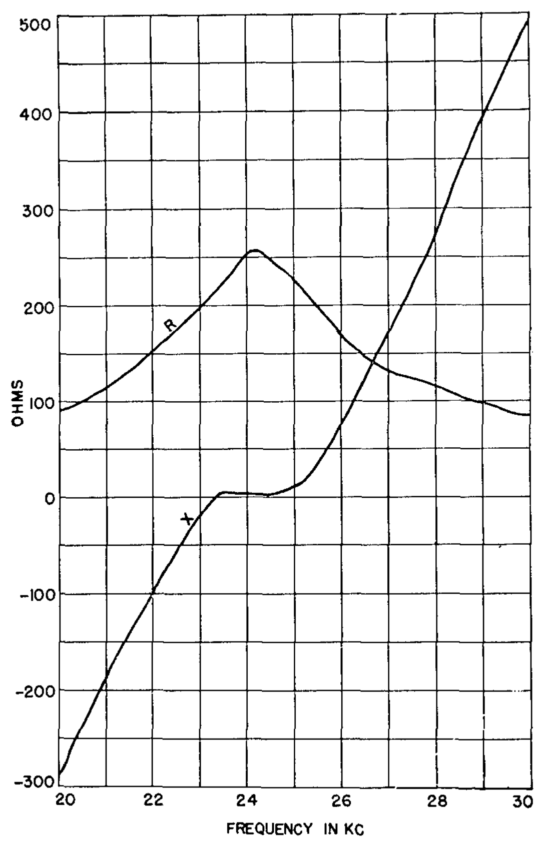
With the results of the various tests and these suggestions, the design of SOD equipment was reduced to the following fundamentals by UCDWR: (1) a circuit designed to transmit



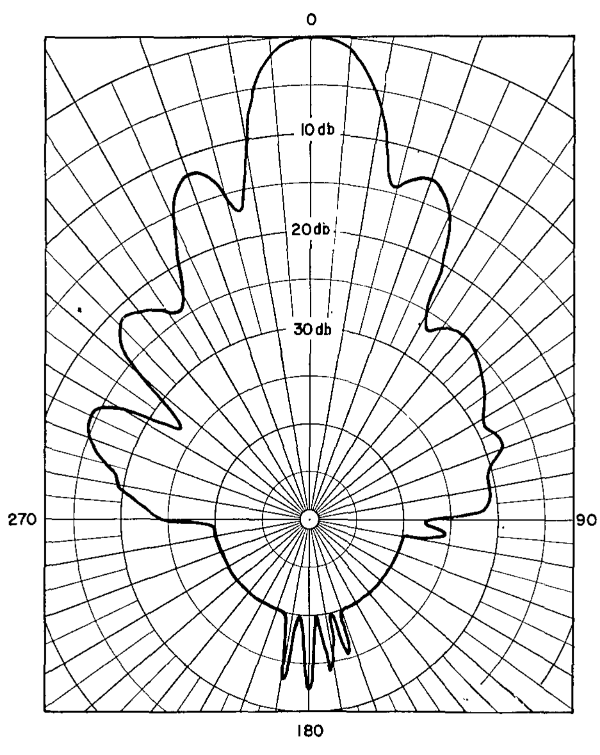
A. Receiver open-circuit voltage response.



B. Transmitter response with constant voltage input.



C. Complex impedance.



D. Directivity pattern in the horizontal plane at 24 kc. The pattern in the vertical plane is essentially the same.

FIGURE 19. JB4Z transducer characteristic curves.

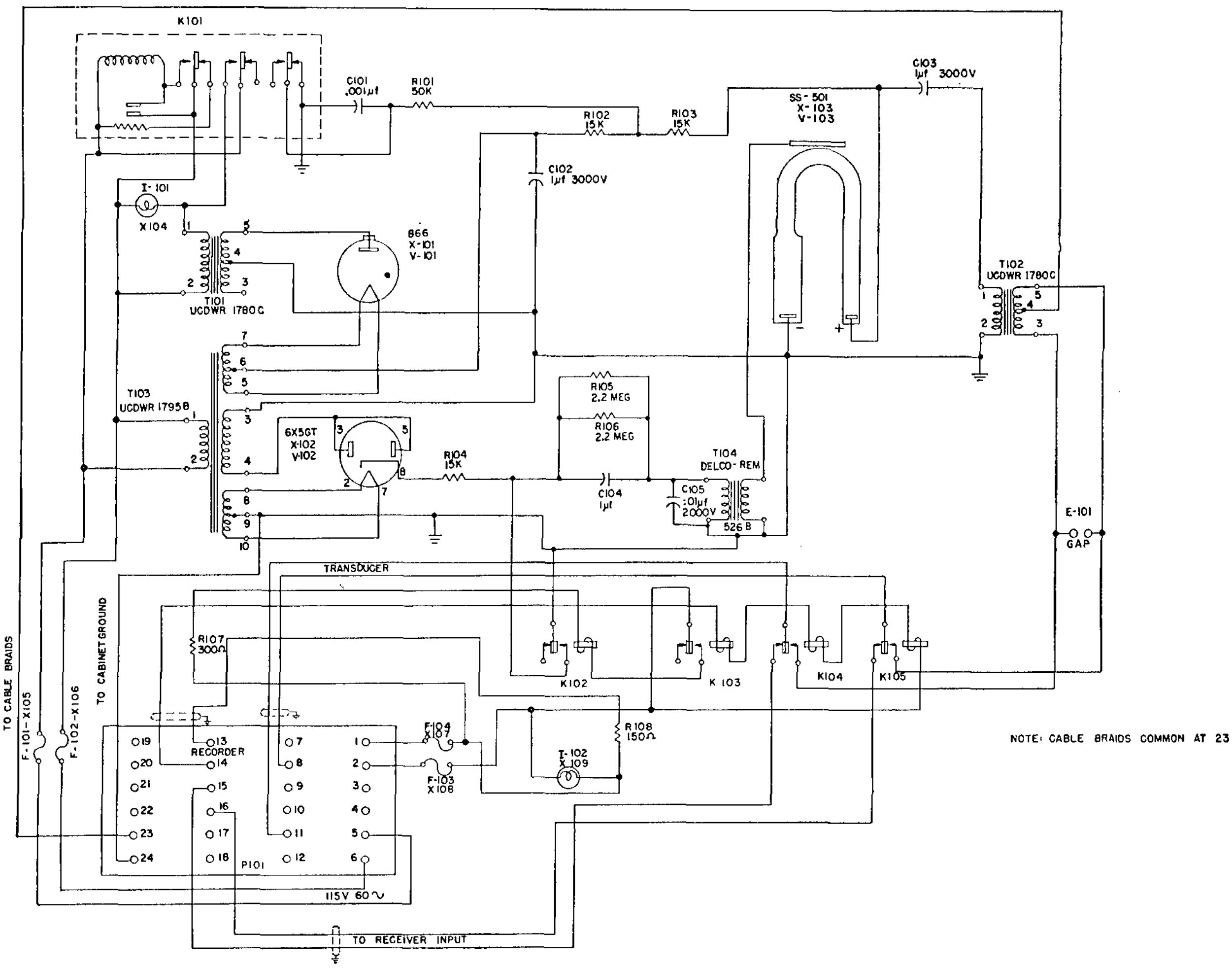


FIGURE 20. Schematic diagram of 24-kc spark gap transmitter.

extremely short pulses with a maximum of instantaneous power, (2) a receiver circuit having specialized characteristics capable of receiving the echo, and (3) a transducer capable of handling a high-powered pulse transmission.

8.8 EXPERIMENTAL 24-KC MODELS

The first model, closely following the suggestions made by Dr. Willis, was designed to provide maximum range. Although it provided much useful design data, trouble was experienced with transducer arc-over.

A second model was therefore designed which provided a better transducer, greater power, and higher receiver sensitivity.

TRANSDUCER

A JB4Z transducer having an ADP crystal array mounted in a standard J size case was used. The beam pattern in both horizontal and vertical planes was approximately 16 degrees at the 6-db down points. Characteristic curves are shown in Figure 19.

TRANSMITTER

In the transmitter design, cognizance was taken of the results obtained by the British using a short, exponential-decay pulse and this type of transmission was adopted. (See Figure 20.) The generation of the pulse may be followed by referring to the block diagram of

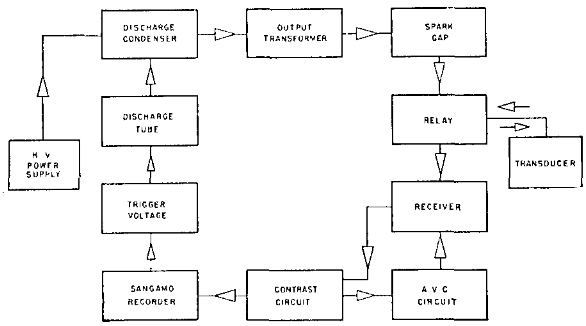


FIGURE 21. Block diagram of SOD spark gap system.

Figure 21. The amplified pulse from the recorder keying relay triggers a discharge tube. This in turn discharges the large capacity condenser, which is charged between pulses from the high-voltage power supply. The condenser's discharged energy is coupled through a transformer to the output circuit.

The output circuit consists of a quenched spark gap, relay, and transducer. When the voltage from the output transformer rises, the voltage within the transducer circuit builds up to a maximum value (approximately 2.5 kv), at which instant the spark gap breaks over, causing the circuit to oscillate. The predominating frequency is 24 kc. After the discharge, the relay connects the transducer to the receiving circuit.

The length of the pulse thus obtained was inherently stable at ⅓ msec long when decayed to the value of $1/e$. Analysis of the pulse indicated a broad band of frequencies present, centered around 24 kc. Peak power of the pulse was approximately 118 db above 1 dyne per sq cm at one meter.

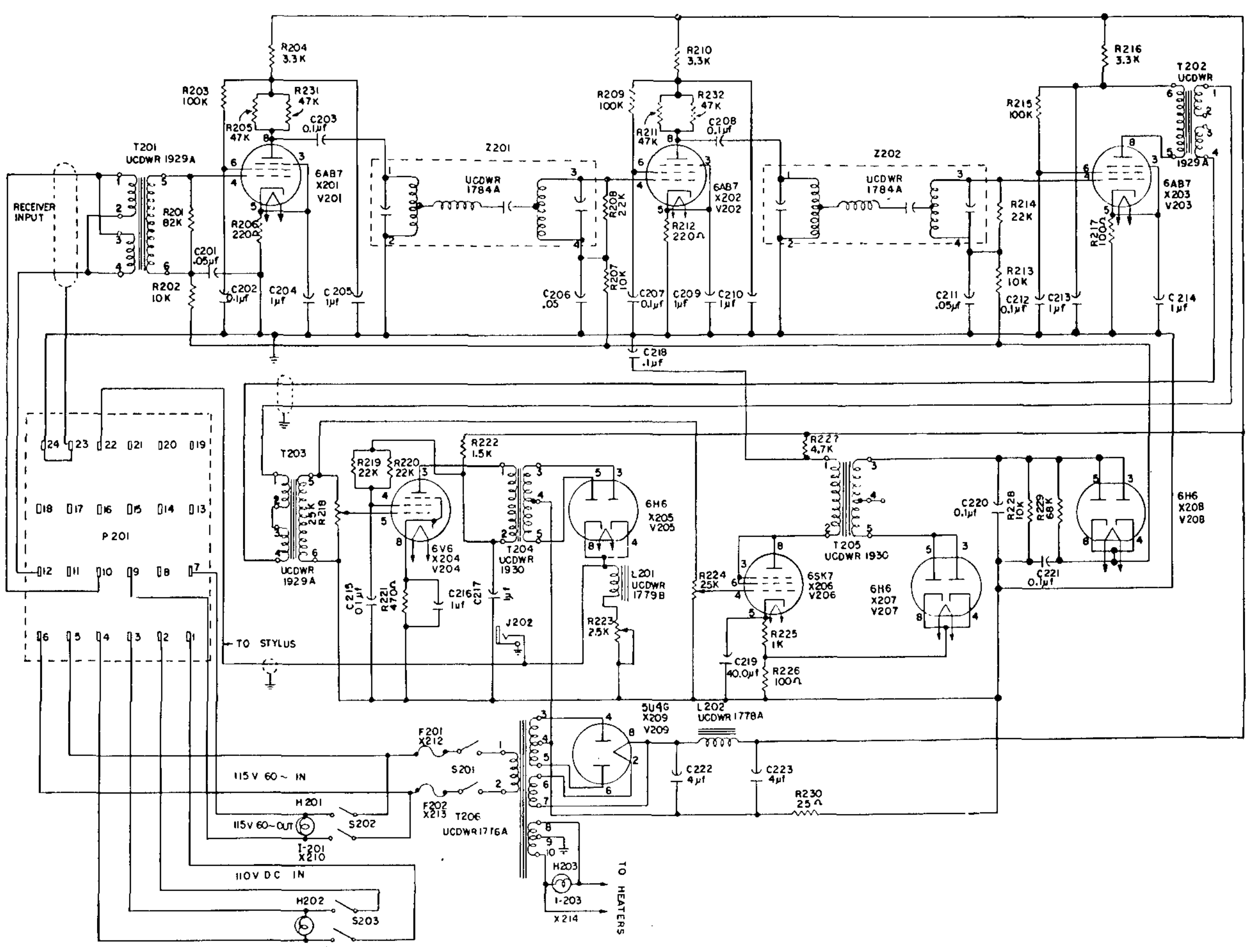


FIGURE 22. Schematic diagram of 24-kc SOD receiver.

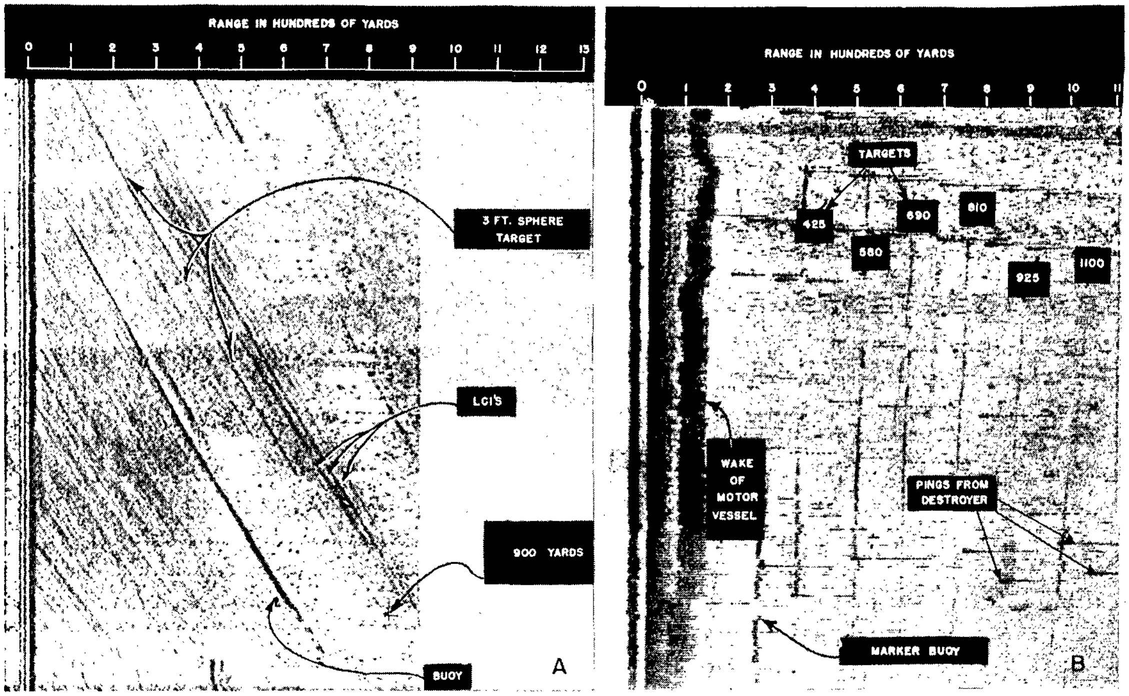


FIGURE 23A. Recorder trace of preliminary model SOD, harbor test.
FIGURE 23B. Recorder trace of preliminary model, sea test.

RECEIVER

The receiver was designed to possess wide band-pass and high-gain characteristics. The circuit consists of three stages of amplification with appropriate filters between stages, an *automatic volume control* [AVC] circuit, and a subtraction unit (see Figure 22). Because of the short length of the received pulse, a wide band-pass is necessary for echo reception. Consequently, the receiver response is fairly flat from 20 to 30 kc at the 3-db down points. The overall gain of the receiver is about 108 db. This amount of amplification is sufficient to satisfactorily mark the recorder paper under normal receiving conditions. The receiver output is applied directly to the stylus of the Sangamo recorder.

The AVC circuit has a time constant of 7.5 msec which allows the receiver to maintain a relatively constant background presentation on the recorder by compensating for reverberation decay. However, any short pulse superimposed on the reverberation is not affected because of the long time constant.

The subtraction unit is a network of inductance, capacitance, and resistance whose primary function in the receiver is to subtract the large d-c component present in the receiver's output, leaving only the short-pulse signals. The filter is resistance-tuned to the time constant of the pulse being received.

PRESENTATION

A standard Sangamo recorder (type CAN-55100A) was converted to a paper speed of 0.625 in. per minute on the 1,500-yd scale. This change resulted in better legibility of the recorder trace and greater clarity of target echoes. If the paper is fed at a slow rate so that successive traces nearly overlap, the target outlines are relatively sharp. Because the receiver's output was fed directly to the recorder stylus, the standard amplifier section of the recorder was removed. Sangamo electrochemically sensitive paper and a standard narrow stylus were used.

PERFORMANCE

The predominating frequency of the transmitted pulse was 24 kc with sidebands between 20 and 30 kc. This type of wide-band transmission tends to give smoother reverberation decay than a normally shaped single-frequency pulse.

Test results of this equipment in San Diego harbor showed that targets, both large and small, could be consistently picked up at ranges in excess of 600 yd. It was found that the spark-generated pulse is also capable of piercing wakes more easily than can pulses of 50 msec (or longer) duration (see Figure 23A).

Final sea tests were conducted from aboard an LCM, during which the SOD located both 8-in. triplanes and 3-ft spheres beyond ranges of 1,000 yd (see Figure 23B).

8.8.1 Model I (500) SOD

GENERAL CHARACTERISTICS

Following evaluation of the 24 kc-preliminary model SOD, which had been of temporary breadboard construction, another apparatus was assembled with the same general characteristics but built to Navy specifications. This is known as Model I (500) SOD.

The transmitter and receiver were enclosed in a QLA cabinet and chassis. Circuit details of the receiver, transmitter, and recorder are given in the preceding section on the 24-kc preliminary model SOD (see Figures 20 and 22).

PERFORMANCE

In April 1945, the Model I SOD was installed aboard a submarine for evaluation and tests (see Figure 16). It was proposed that this SOD be used in conjunction with the QLA sonar gear as a long-range searching device. It was found that the equipment could be used to conn the submarine through a mine field while both devices were operated. The maximum reported range of the SOD in detecting mines was approximately 1,500 yd. By reference to Figure 24, 1,500-yd contacts on a group of six mines may be seen.

Data and experience secured under actual submarine operating conditions suggested improvements which were later incorporated in the improved Model II SOD, a description of which is given in the following section.

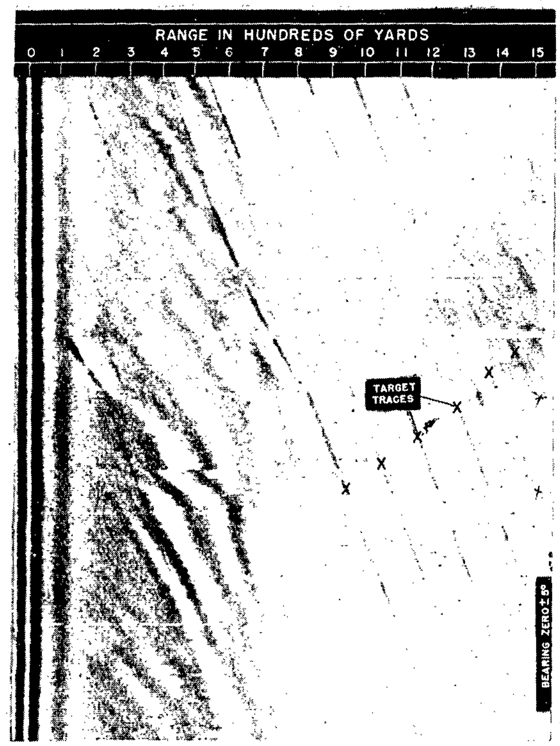


FIGURE 24. Submarine recorder traces of multiple targets.

8.9 MODEL II (501) SOD

GENERAL CHARACTERISTICS

Model I submarine tests had shown that some form of bearing indicator would be a definite asset. As a result, a fiducial bearing indicator was developed as a special feature of the Sangamo recorder. The receiver gain was increased as a result of redesign of the band-pass amplifier characteristics. The AVC dynamic range was slightly increased, and the overall frequency response of the subtraction unit was improved.

The Model II transmitter is similar to that used in Model I (see Figures 21 and 22) with the exception that the relay changeover for the transducer (in addition to the keying relays) is installed on the transmitter chassis.

Receiver

The schematic diagram of the Model II SOD receiver is shown in Figure 22. A slight increase in sensitivity was obtained by the incorporation of higher Q inductance in the filter circuits. General mechanical construction was improved by minor design refinements.

Bearing Indicator

The bearing indicator, shown in Figure 25, incorporates a selsyn-drive helical drum in the recorder, rotating in azimuth simultaneously

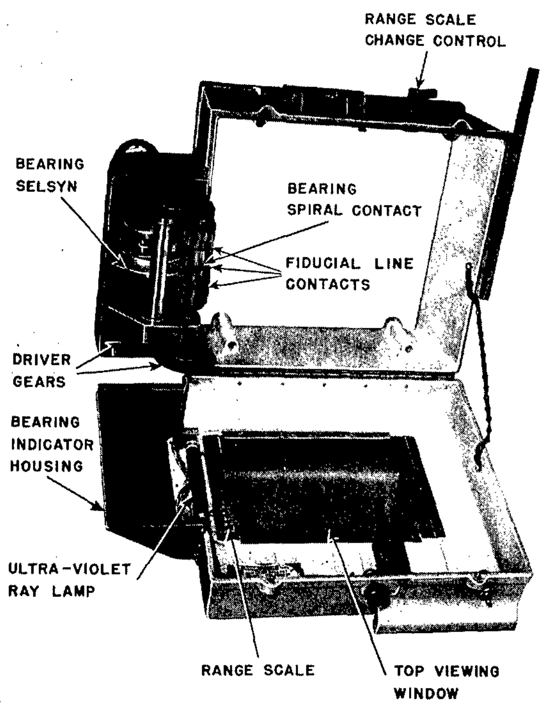


Figure 25. Model II (501) SOD bearing indicator mechanism.

with the rotation of the transducer. This arrangement provides linear representation of the bearing of the transducer, and shows 0-, 90-, and 270-degree fiducial (reference) lines upon the record (see Figure 26). These functions are performed by the same stylus which records target (echo) indication.

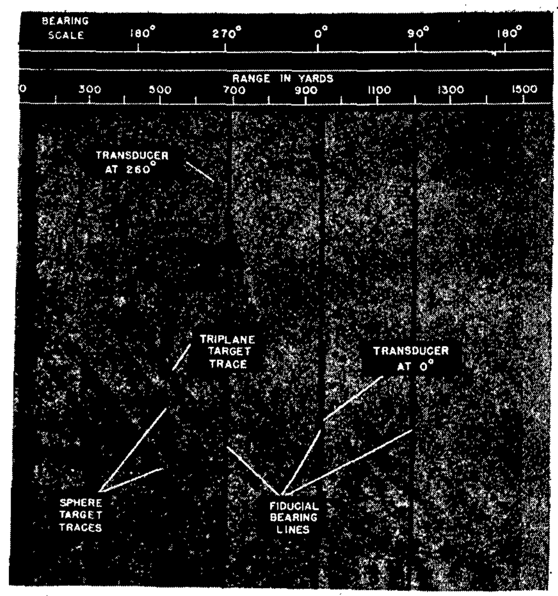


Figure 26. Model II (501) SOD recorder trace showing fiducial bearing lines.

Performance

Sea tests with this system showed that a 3-ft sphere could be contacted over 1,000 yd. In relatively shallow water, mine contacts were made at maximum ranges of 800 yd.

Recommendations

Although Model II SOD is the last 24-kc device built at the date of this report, research is being continued towards the development of a 24-kc *sector scan indicator* [SSI] in an effort to give *position plan indication* [PPI]. A proposal has been made to use a recorder paper width of 18 in. for the 1,500-yd range scale, as opposed to the present width of 6 in. to permit better definition because of the higher stylus speed.

8.10 90-KC SOD

Description

While the various 24-kc SOD devices were being developed, a 90-kc SOD device was constructed to investigate the feasibility of echo ranging in the 80- to 90-kc band.

TRANSDUCER

A UCDWR type FE2Z transducer, designed for operation in the vicinity of 90 kc, was made up of an array of ADP crystals, inertia driven in air or Freon gas, and provided with a foam rubber backing (see Figure 27). At 90 kc, the horizontal lobe pattern is fairly broad, having a width of 16 degrees at the 3-db down points; the vertical pattern is quite narrow, being 5 degrees wide at the 3-db down points. The pattern is lobe-suppressed in the horizontal plane only. Response curves indicated high efficiency in the 80- to 90-kc band; characteristic curves of the transducer are shown in Figure 28. A tilting mechanism was installed between the transducer mounting and the training column, making it possible to direct the transducer horizontally or vertically and to lock it in position.

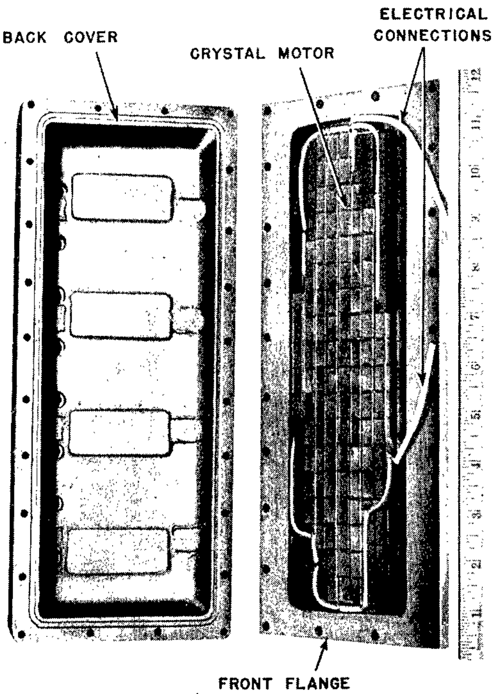


FIGURE 27. FE2Z transducer.

TRANSMITTER

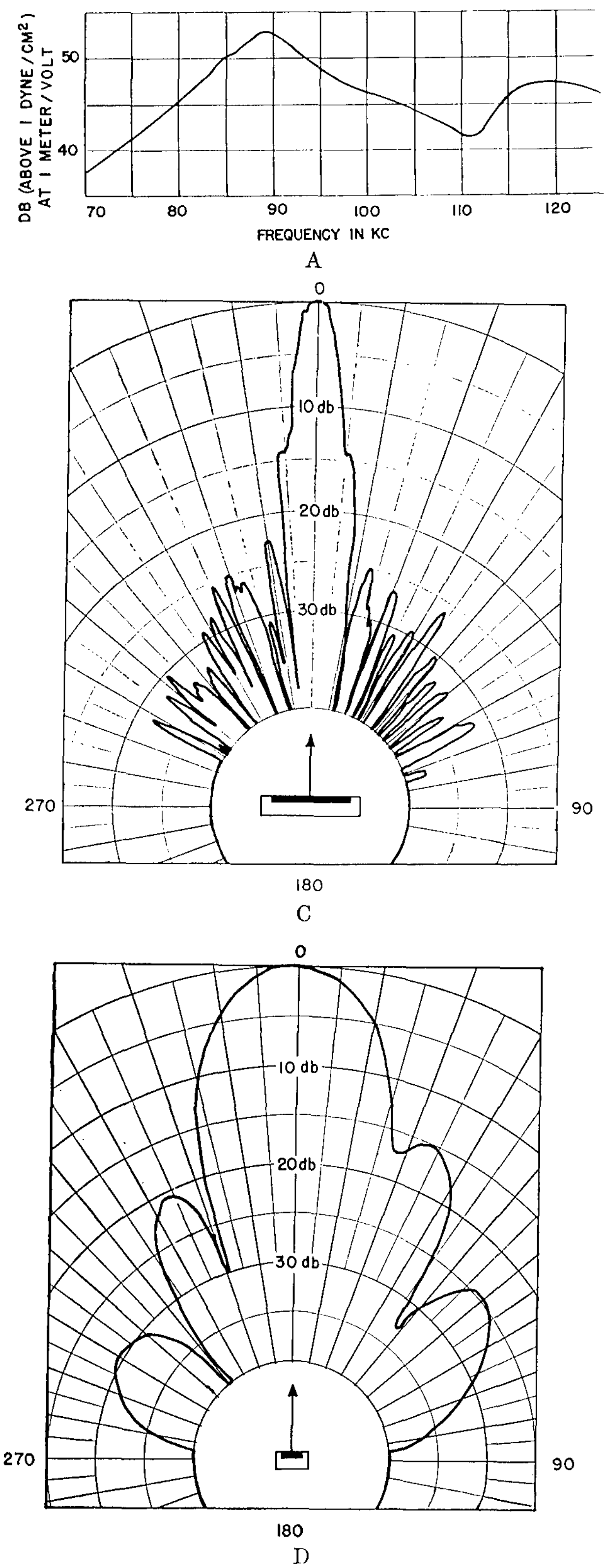
The transmitter consists of a pulse generator (Figure 29) and power amplifier (Figure 30) with associated power supplies. The pulse generator supplies a modulated pulse to the power amplifier and includes the transducer switching relay.

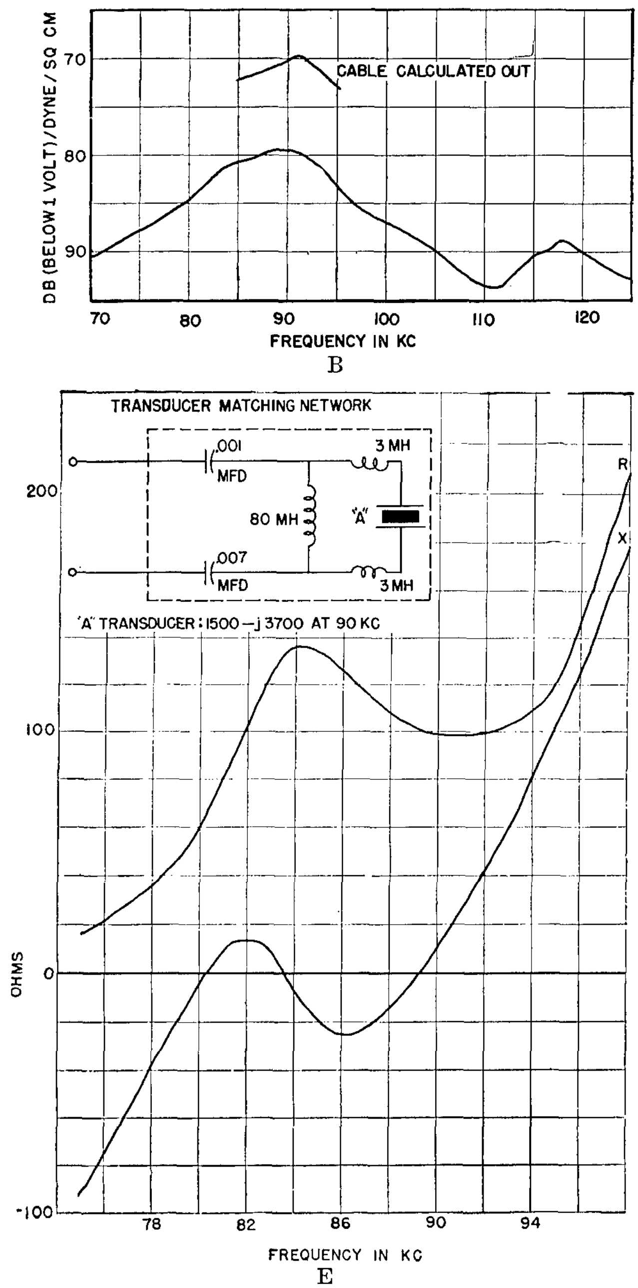
The circuit operation may be followed by reference to the block diagram of Figure 31. The pulse rate oscillator (range determining means) is built around an 884 thyratron and produces a pulse rate continuously variable from 1 to 50 cycles per second. The pulse is shaped by the relay interval timer to a square wave form of adjustable period; this adjustment also determines how long the switching relay remains in the "transmit" position. From the relay interval timer, the pulse is applied to the relay control circuits where it is amplified to actuate the relay. The pulse is also applied to the pulse delay timer, where it is adjustably delayed to insure the relay time to operate before the outgoing pulse arrives at its contacts. The delayed pulse then goes to the pulse timer, where the final pulse length is determined. Three pulse lengths (1.4, 1.9, and 3.0 msec) are available by means of the selector switch in the plate circuit of the pulse timer. The square wave pulse from the pulse timer is used to key the multivibrator oscillator, which modulates the pulse with approximately 90 kc. The frequency of transmission is variable from about 70 to 105 kc by means of the potentiometer in the oscillator grid circuit. After passing through the balanced cathode follower, the pulse is fed to the power amplifier, a conventional push-pull circuit (Figure 30). From the power amplifier, the signal is delivered to the transducer cable terminals. The power input to the transducer cable terminals varied from 100 to 400 watts. The sound pressure in the water was found to be approximately 109 db above 1 dyne per sq cm at 1 meter.

A later addition was a switch connected after the pulse rate oscillator which permits obtaining the initiating pulse from the Sangamo recorder keying contacts in place of the 884 thyratron.

RECEIVER

The first receiver was a three-stage amplifier with a diode rectifier which delivered the





A. Transmitter response with constant voltage input.
B. Receiver open circuit voltage response measured at the end of a 35-ft cable.
C. Directivity pattern in the vertical plane at 90 kc.
D. Directivity pattern in the horizontal plane at 90 kc.
E. Complex impedance measured at the end of a 37-ft cable with matching network between unit and cable.

FIGURE 28. FE2Z transducer characteristic curves.

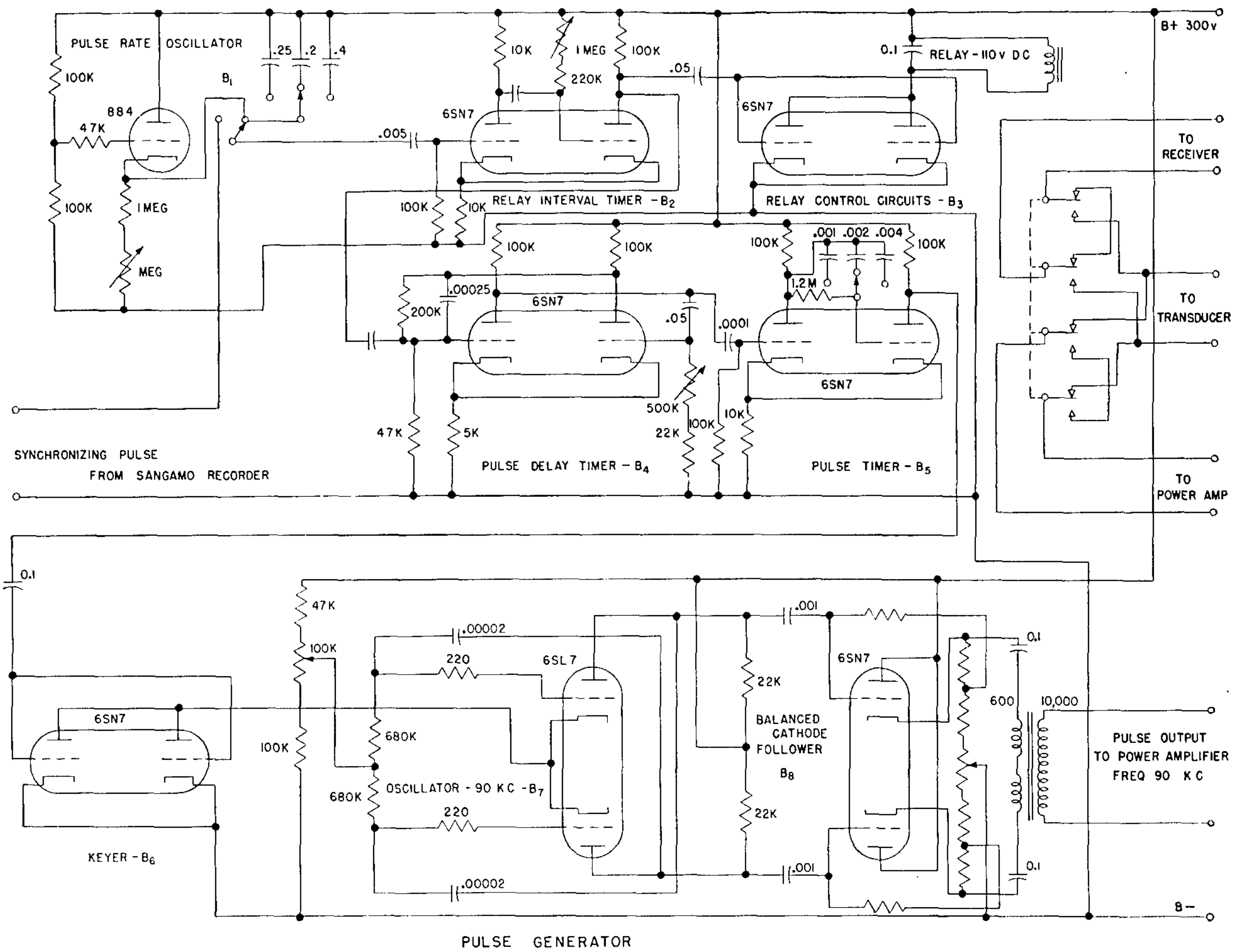


FIGURE 29. Schematic diagram 90-kc SOD pulse generator.

signal to the CRO. Later, an improved version, incorporating a TVG circuit (see Section 2.2), was constructed. A schematic diagram of the final receiver is shown in Figure 32; its frequency characteristic is shown in Figure 33.

PRESENTATION

Received signals are applied to the vertical amplifier of an A scan CRO having a long-persistence screen (see Figures 31 and 34). A slow linear sweep was provided to make signal sweeps as long as 1.3 sec possible. A cathode follower (see receiver schematic, Figure 32) was incorporated to couple the signal from the receiver to the Sangamo recorder stylus at the proper voltage without affecting the CRO presentation. The recorder was modified by instituting a slow paper speed of 0.625 in. per minute. Later, a fast stylus, high-speed Sangamo recorder with a maximum range of 600 yd was also furnished. Sample traces from the slow- and high-speed recorders are shown in Figure 35.

PERFORMANCE

A number of test runs were made in San Diego Bay using mooring buoys, spaced 200 yd apart in 40 ft of water, as targets. Figure 35A shows the results of one test made with the long pulse (3 msec) and slow paper-speed recorder. The results of the second test, made with the high-speed recorder, are shown in Figure 35B.

Tests were also made at sea in water varying in depth from 100 ft to 100 fathoms using

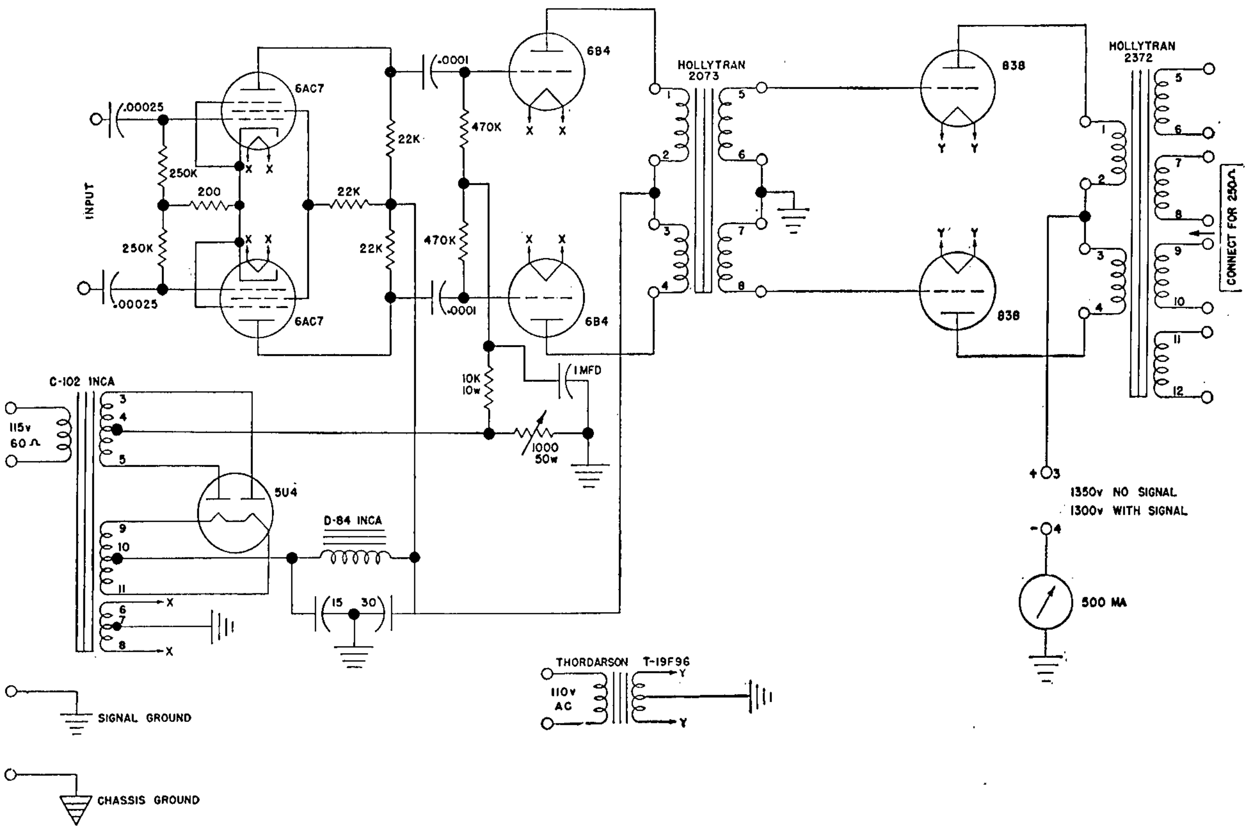


FIGURE 30. Schematic diagram of 90-kc SOD power amplifier.

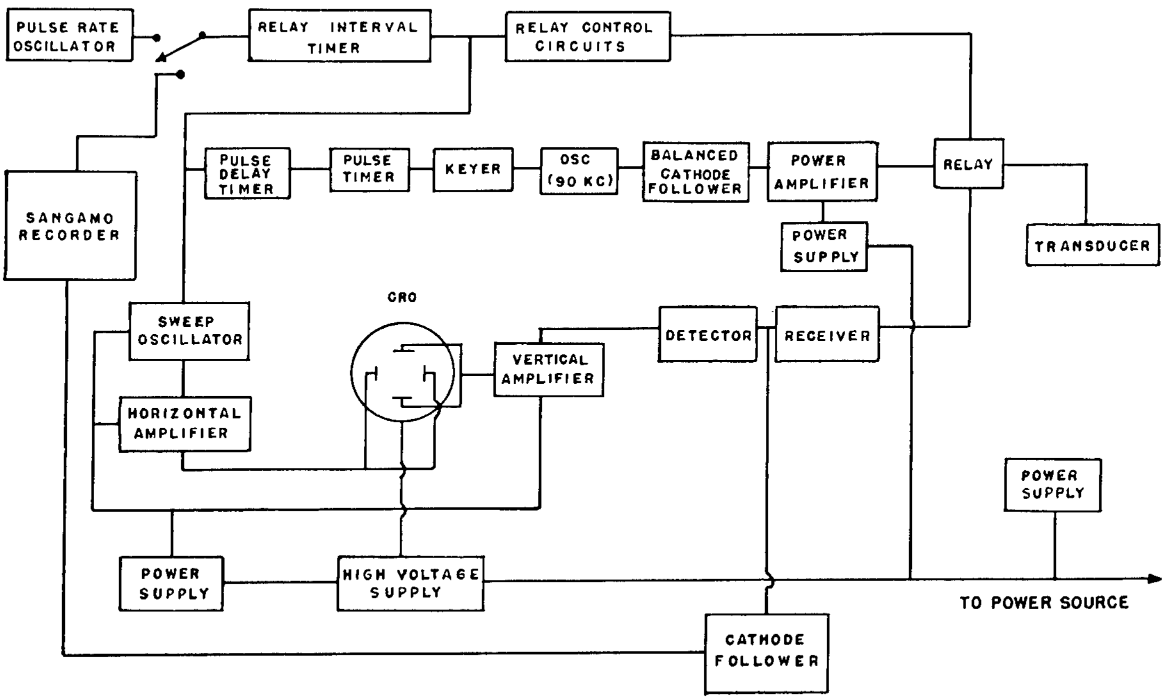


FIGURE 31. Operational block diagram 90-kc SOD apparatus.

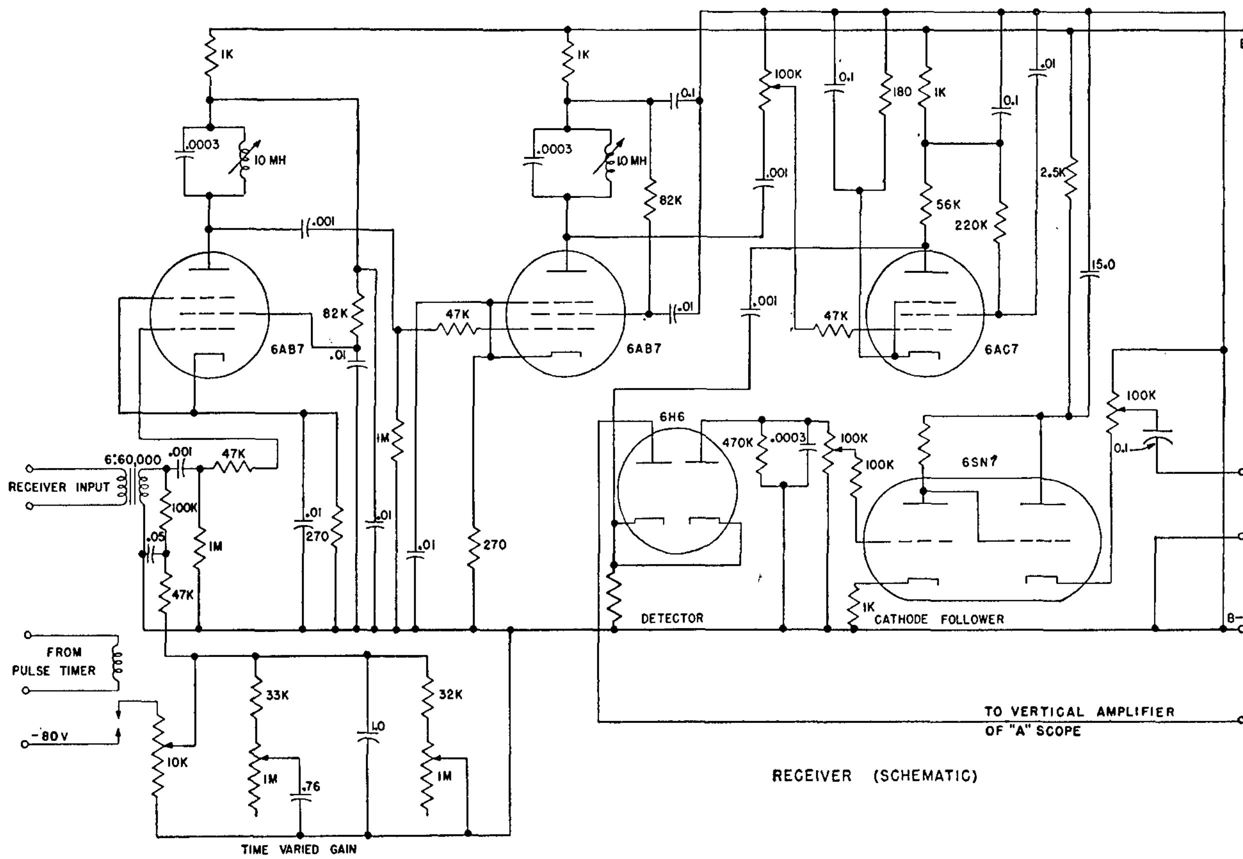


FIGURE 32. Schematic diagram 90-kc SOD receiver.

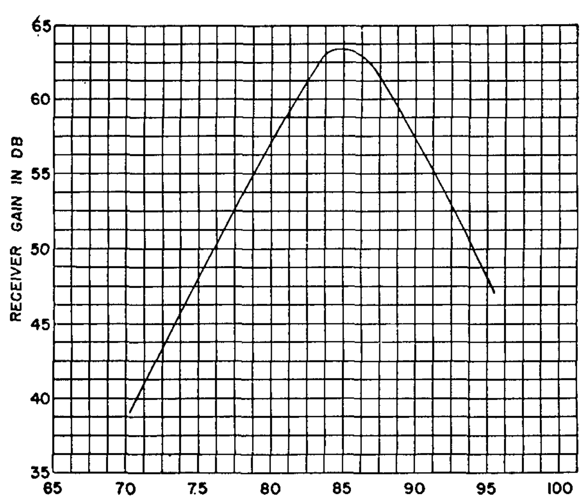


FIGURE 33. Frequency response curve of 90-kc SOD receiver.

standard 3-ft spheres as targets. The results of one test, shown in Figure 35C, show that the sphere was not detected until a vessel, traveling at high speed between the test vessel and the target, had passed. In the second run (Figure 35D), with no interfering wake, the target was identified at 350 yd.

EVALUATION

Although the 90-kc SOD had various drawbacks, it was felt that they were more than compensated by the advantages of the system. The equipment constructed for this investigation was designed to give maximum control of the variables of the problem rather than optimum operation. On the basis of the test runs

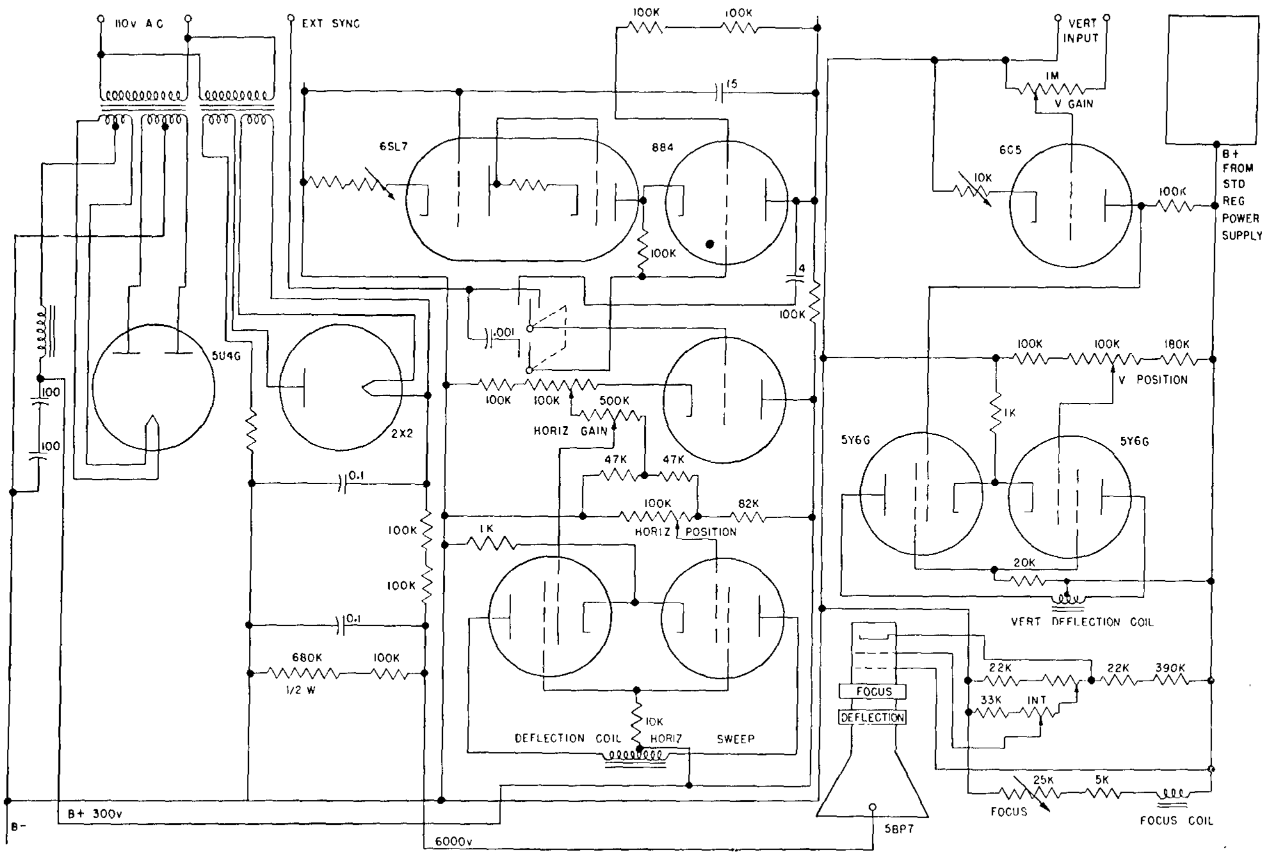


FIGURE 34. Schematic diagram of 90-kc SOD oscilloscopic circuits.

only, the following conclusions may be drawn.

Pulse Length. In the few tests made, the 3-msec pulse resulted in the greatest range. It was felt that the most useful device for indication of maximum range through noise and reverberation should have a continuously variable pulse length from 0.25 to 3.0 msec.

Signal Frequency. As predicted by theoretical considerations, operation at this frequency (80 to 90 kc) decreased the maximum range.

Power in Water. The power in the water was low. This could be made higher by efficient amplifier design. However, a considerable increase in power would be necesary to increase maximum range by an effective amount.

Transducer Directivity. The directivity pattern of the FE2Z transducer makes operation difficult on a rolling ship in a heavy sea. On a reasonably stable platform, the 5-degree vertical beam might be more efficient. Further improvement might be made by lobe suppression in the vertical plane and a reduction of the horizontal beam to about 10 degrees.

Presentation. The fast-stylus recorder presents a much more readable result than the slow paper-speed, long-range recorder, and it is recommended when use of the recorder is a necessity. A PPI with a high resolution is the obvious solution, but presents a tremendous engineering problem. The A scope monitor proved extremely valuable for tuning the equipment and gave a much higher degree of resolution than the recorder traces. This is shown in Figure 36. A dual installation of PPI and A scan would be an extremely effective manner of presentation.

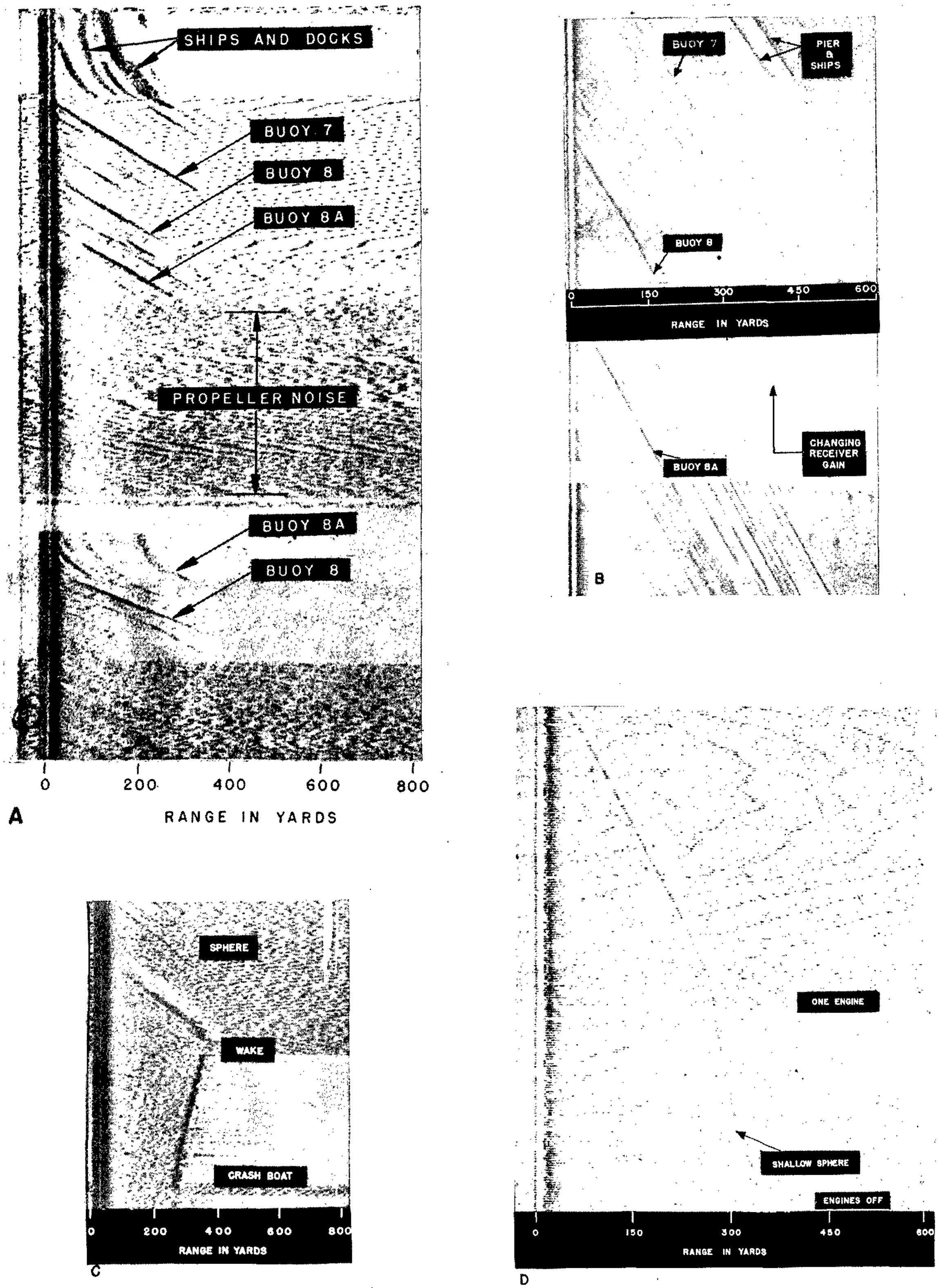


FIGURE 35. Recorder traces of 90-kc SOD tests.

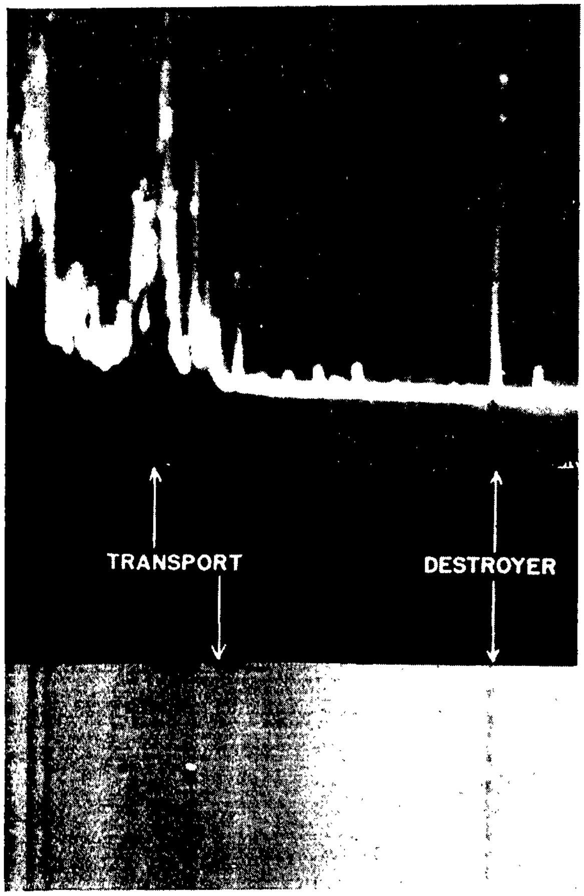


FIGURE 36. Comparison between A-scan CRO and recorder trace presentation.

Underwater Sound Direction and Range System [USDAR]

USDAR is a small, hand-held device which is capable of giving a qualitative indication of direction and distance of underwater obstacles at a range from approximately 5 to 100 feet. The device, similar in appearance to a flashlight, is self-contained, with the exception of a battery box and headphones. A single quartz crystal is used for both transmitting and receiving a continuous frequency-modulated signal. Distance to the object is indicated by the apparent pitch of a tone obtained by heterodyning the transmission and echo signals. Direction is indicated by orienting the device for maximum signal amplitude in the phones. USDAR was developed by the RCA laboratories.

8.12 INTRODUCTION

Before and during coastal amphibious landing operations, underwater objects in shallow water such as mines, reefs, and other obstacles must be located. Prior to the development of USDAR, these obstacles could be located only by men walking or swimming in the water. Attempts to adapt a standard Army land mine detector for this purpose were unsuccessful because of its limited range and the difficulty of handling in waves and surf.

There was need for an instrument which was small, portable, waterproof, and operable in fairly shallow water by swimmers and divers. Such an instrument was also to be operable overside from a small boat. The system devised consisted of a midget narrow-beam echo-ranging system employing a sine-wave frequency-modulated signal which is continuously projected into the water through a small crystal transducer. The reflected signal is received by the same transducer and mixed in a detector with the transmitted signal to give a warbling beat frequency, audible in earphones, whose apparent pitch is dependent on the distance of the reflecting object.

Various models employing frequencies of 250-, 500-, and 1,000-kc were tried. Best results were obtained with a 500-kc model, the USDAR Model 500 A, which was adopted and put into pilot production. Although these units did not see large-scale use during the war, their ability to locate very small objects under difficult conditions should make them useful as an underwater sound "flashlight" for many underwater operations.

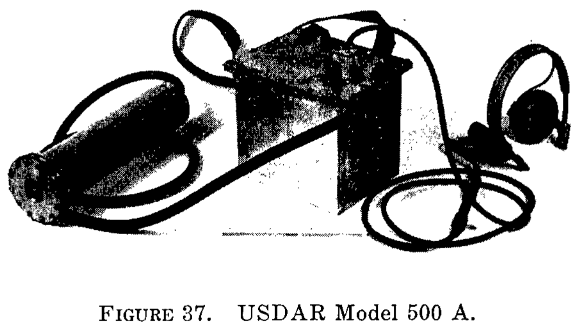


FIGURE 37. USDAR Model 500 A.

Certain suggestions for improvement, including the use of a sawtooth modulation to provide a single-frequency tone instead of the present warbling tone and an ADP transducer, have been proposed and are scheduled for further investigation.

8.13 TECHNICAL DEVELOPMENT

USDAR 1000

The first model included a low-frequency oscillator (12 cycles per second), a reactance-tube modulator, a high-frequency oscillator (1,000 kc per second), a detector, a two-stage audio amplifier, and two quartz crystal transducers (one for transmitting and one for receiving). These components, together with batteries for several hours of operation, were assembled in a portable case.

It was soon decided that two transducers were unnecessary and the detector system was changed so that a single crystal transducer was used for both transmitting and receiving.

A second alteration increased the high-frequency response of the audio channel with a view to increasing the range of the unit.

In the second model attempts were made to improve the sound output. To this end a circuit was developed to give a sawtooth modulation of the high frequency, with the expectation of obtaining a more nearly constant tone in the headphones (for a given distance).

Both these models performed satisfactorily, although it was found difficult to keep them on the target, because of the narrow beam.

USDAR 500

This unit was identical with the first Model 1000, except that it was designed to operate in the 500-kc band. Tests showed some improvement over previous models, particularly a gain in maximum range. In an effort to improve the overall performance, it was decided to build a new unit incorporating the following.

1. Increased high-frequency power.
2. Broader directivity (achieved by using a crystal whose diameter is one-half the usual dimension).
3. Increased high audio-frequency gain.
4. Oscillator frequency of 500 kc.
5. Audio signal to be centered at 500 c at 5 ft.
6. Vibrator power supply with external battery in waterproof case.
7. Heavier unit case.

It was also decided to investigate the problem of waterproof headphones for use in the surf. As a result a waterproof modification of a Western Electric headset was developed, which was submersion-proof and incorporated a soft rubber cup to cover the ears. The cup served to prevent airborne sound and water from getting into the ears. The modified headphone ranged from 2 to 10 db less sensitive than the unmodified set.

Alterations of the audio system resulted in approximately a 20-db increase in gain in the high-frequency range. The overall result with the modified amplifier and headphones was a 10-db increase in sound pressure response at the higher frequencies.

USDAR 250

The USDAR 250 unit operated in the 250-kc region and in construction was the same as the original USDAR 1000 and 500 units except for the size of the crystal. This was 2 in. in diameter, compared to a 1-in. crystal used in the 500 model and ½-in. in the 1000 model. The performance of the 250 unit was somewhat better than that of the 1000 unit, and after changes in the values of resistors and capacitors in the detector circuit it showed a slight improvement over the original 500 model. However, this difference might have been overcome by applying the changes made in the 250 unit to the 500 USDAR.

San Diego Models

The University of California Division of War Research group in San Diego developed several devices similar in nature to the USDAR unit. A small transducer, consisting of a mosaic of ADP crystals (instead of a quartz crystal), was used in the following devices.

1. A 250-kc USDAR unit using the same electric circuit as the RCA USDAR-1000 series.

2. A 118-kc USDAR using linear (sawtooth) frequency sweep. The circuit for this unit was developed in San Diego.

3. A shock-excited pinging type of USDAR. The transducer in this unit was pulsed periodically by applying a sawtooth voltage from a gas tube relaxation oscillator. The transmitted and received pulses were observed on an oscilloscope.

4. An echo-keying USDAR unit employing a blocking oscillator type of circuit. (No further data available.)

Comparative tests between the first three units and an RCA USDAR Model 500 A (see next section) gave range results which agreed fairly closely. The linear frequency sweep model gave a signal which had the sound of a nearly constant tone interrupted periodically by a loud, sharp thump, presumably due to the sawtooth "fly back."

The pinging type worked well at short distances although the use of the oscilloscope indicator restricted the intended conditions of use.

USDAR 500 A

The 500-kc model described earlier was modified to incorporate the original directional characteristic (narrow beam), the new audio characteristic, and a separate waterproof battery box. The vibrator supply was abandoned. The high-frequency swing was made as large as feasible, and more high-frequency power was obtained. The USDAR Model 500 A was then accepted as the final model.

8.14 DETAILED DESCRIPTION OF FINAL MODEL

Principle of Operation

Figure 38 shows the block diagram of the USDAR Model 500 A. A separate transmitter and receiver are shown to simplify the explanation, although the actual device uses a single crystal which serves both purposes. An audio-frequency (a-f) oscillator operates at 12 cycles per second and is used to drive a variable reactance tube. This in turn serves to vary the frequency of a high-frequency (h-f) oscillator which oscillates at 500 kc. The output of the h-f oscillator is applied to a quartz crystal transmitter. Reflected sound, picked up by the crystal receiver, generates a voltage which is applied to a detector. A small amount of the h-f oscillator output is also applied to the detector. The output of the detector is amplified and applied to a pair of headphones.

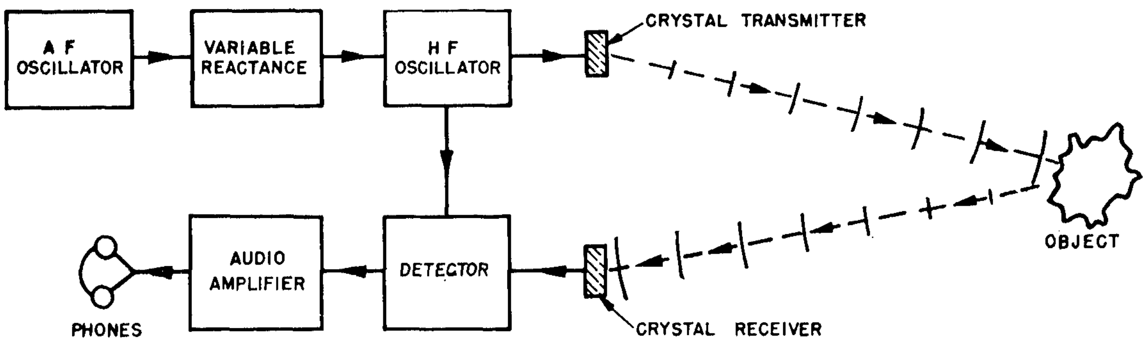


FIGURE 38. Block diagram—USDAR Model 500 A.

In Figure 39 the output of the a-f oscillator is shown as a sine wave. The frequency of the h-f oscillator output, also a sine wave, varies 4,500 cycles above and below its average frequency of 500 kc, at the same rate as the a-f frequency, or 12 cycles per second. The signal from the incoming echo lags behind the h-f oscillator output an amount dependent upon the distance to the object. The audio output frequency, shown as the difference between the outgoing signal and incoming echo frequencies, varies from zero to a maximum, which depends on the distance to the object, at a rate twice that of the a-f frequency. The impression given

by listening to such a signal is a warbled tone of approximate $\frac{7}{10}$ of the maximum frequency.

From the foregoing it is seen that the frequency of the detector output is dependent on the rate at which the h-f oscillator frequency is changed and the distance to the object. It should be noted that the closer the object the

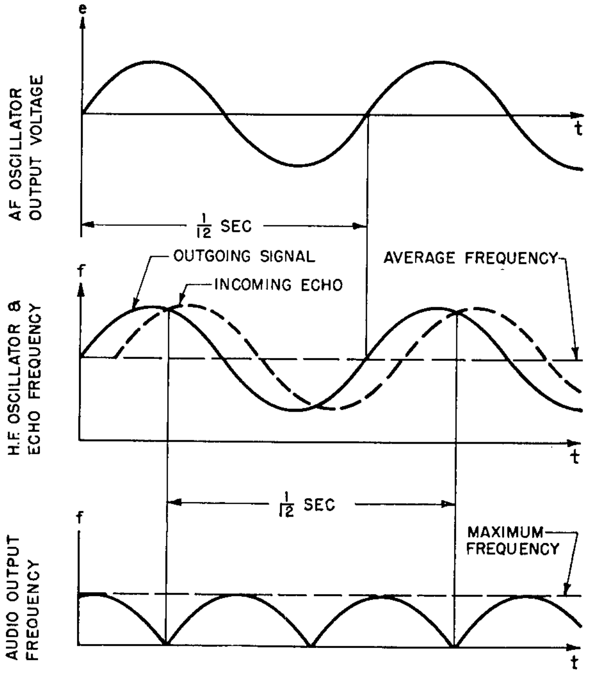


FIGURE 39. Output wave forms.

lower the frequency, within the normal maximum range of approximately 100 ft. The maximum difference frequency of 9,000 cycles per second occurs when the delay between the outgoing signal and incoming echo is 180 degrees which, since the audio frequency is 12 cycles per second, is $\frac{1}{24}$ sec. This corresponds to a range of approximately 100 ft. Beyond that distance the difference frequency becomes smaller, causing an ambiguity in range when compared to distances of less than 100 ft.

The complete device is shown in Figure 37. The unit proper is contained in the cylindrical case. The quartz crystal is seen as a depression in the face of the unit. The rectangular case, containing the batteries, and the phones are waterproof. A side view of the chassis is given in Figure 40.

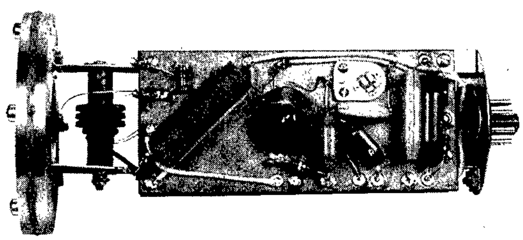


FIGURE 40. Side view of chassis—USDAR Model 500 A.

ELECTRICAL DESCRIPTION

The schematic circuit diagram of the USDAR Model 500 A is shown in Figure 41. The first 1T4 tube is the audio-frequency oscillator. It utilizes a resistance-capacity feedback network in which the phase shift is 180 degrees at the desired frequency of 12 cycles per second.

The second 1T4 is the reactance tube. Its plate voltage is the sum of the B + and the high-frequency alternating voltage across the high-frequency oscillator grid coil. The grid is connected to the plate through a small capacitor. The grid is also connected to ground through a 1,000-ohm resistor and a relatively large capacitor which is essentially a short circuit for the high frequency. The result of this circuit is to impress on the grid a voltage which is 90 degrees out of phase with the voltage impressed on the plate. The resulting plate current will therefore be 90 degrees out of phase with the plate voltage or the equivalent of a capacitor. The amount of plate current (or the effective capacity) in the tube can be changed by varying the grid bias. The desired variation of grid bias is obtained by coupling the low side of the 1,000-ohm resistor to the low-frequency oscillator.

The 1S4 tube is the high-frequency oscillator. It is a form of electron-coupled circuit in which the frequency is controlled mainly by the screen grid-control grid portion of the circuit. The plate circuit is, to a degree, isolated from the grid circuit and has only a minor effect on the frequency. The reactance tube is connected across the frequency-controlling portion of the circuit and varies the frequency in accordance with the signal from the low-frequency oscillator. The 1S4 plate circuit is a tuned trans-

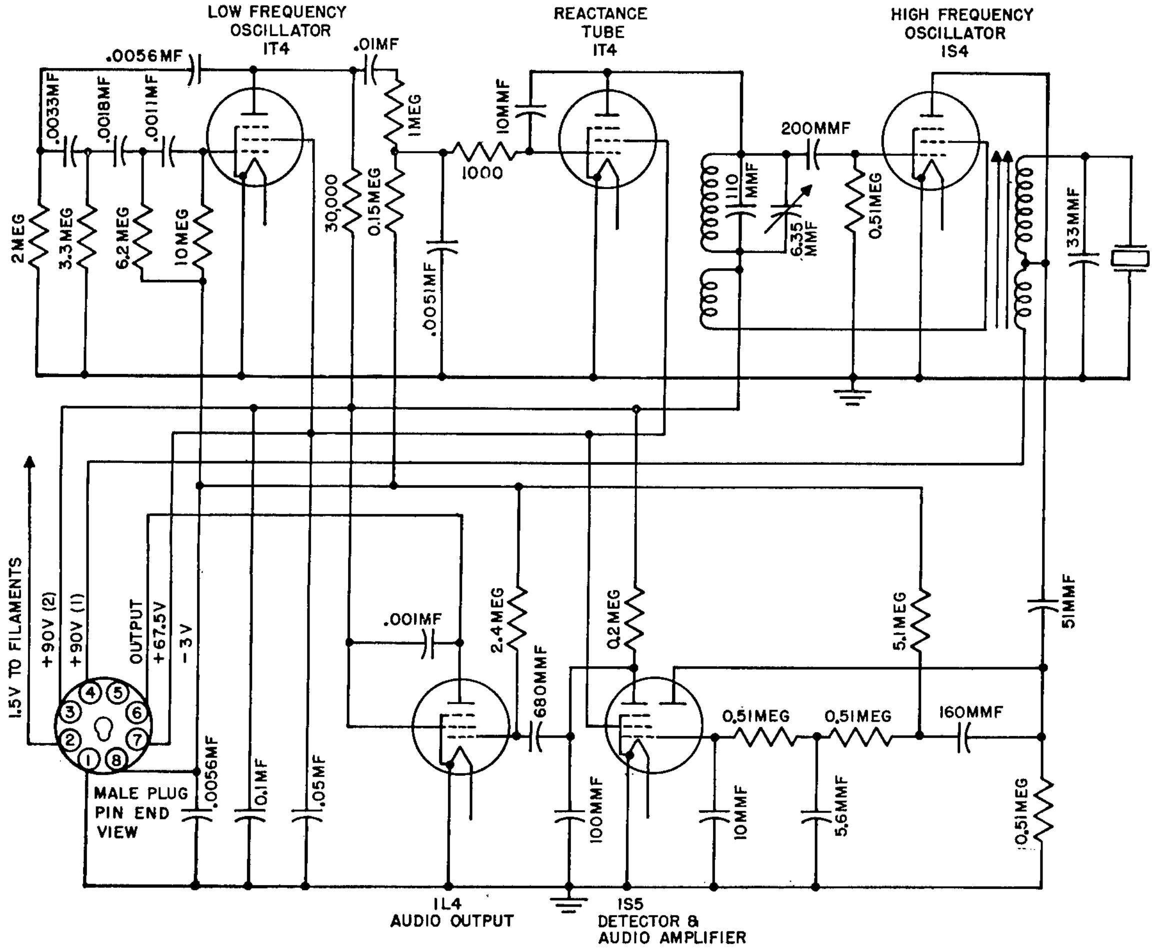


FIGURE 41. Schematic circuit diagram—USDAR Model 500 A.

former which serves to produce a high voltage across the quartz crystal element.

The 1S5 is a combined detector and first audio-frequency amplifier stage. The detector is a diode, the plate of which is coupled to the crystal circuit by a 51-$\mu\mu$f capacitor and connected to ground by a 510,000-ohm resistor. The circuit between the diode plate and the 1S5 grid is a filter to suppress the high-frequency voltage existing in the detector output. The 1L4 is the audio output stage. It is coupled to the 1S5 by standard resistance-capacity means. The 1L4 is pentode-connected and is coupled to the phones by means of a transformer.

Calibration of USDAR Model 500

Figure 42A gives the open-circuit receiving response of the USDAR 500 unit in decibels versus 1 volt for a sound field of 1 dyne per sq cm. The transmitting response of the unit, expressed as sound pressure at a 10-ft distance on the axis in decibels versus 1 dyne per sq cm per volt in series with 72 ohms, is given in Figure 42B. By the addition of 34.3 db to the values in this figure, the transmitting response can be expressed in terms of the pressure at 1-meter distance in decibels versus 1 dyne per sq cm for one available watt from 72 ohms.

Figure 43 shows a directivity pattern for the unit at 495.6 kc. The directivity index is −28.7 db. From this index and the projector response, the transmitting efficiency of the unit was found to be −10.2 db. The minimum measurable signal pressure for a 1-c band, that is, the threshold pressure of the crystal, is 82.7 db below 1 dyne per sq cm (8.7 db below 0.0002 dyne per sq cm).

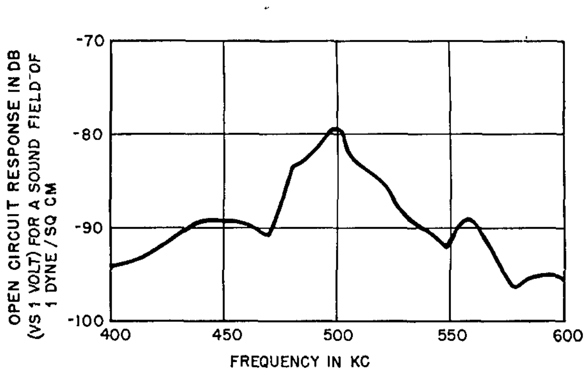


FIGURE 42A. Response of USDAR Model 500 (serial No. 1)—used as a hydrophone.

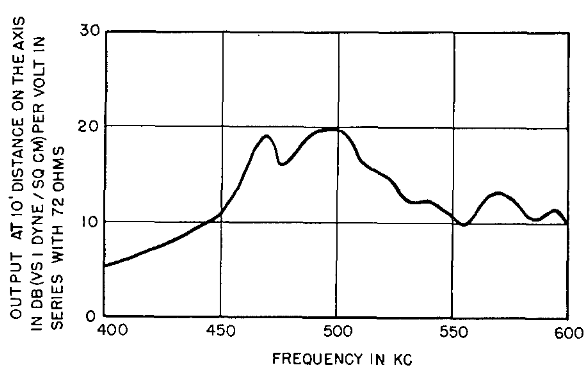


FIGURE 42B. Response of USDAR Model 500 (serial No. 1)—used as a projector.

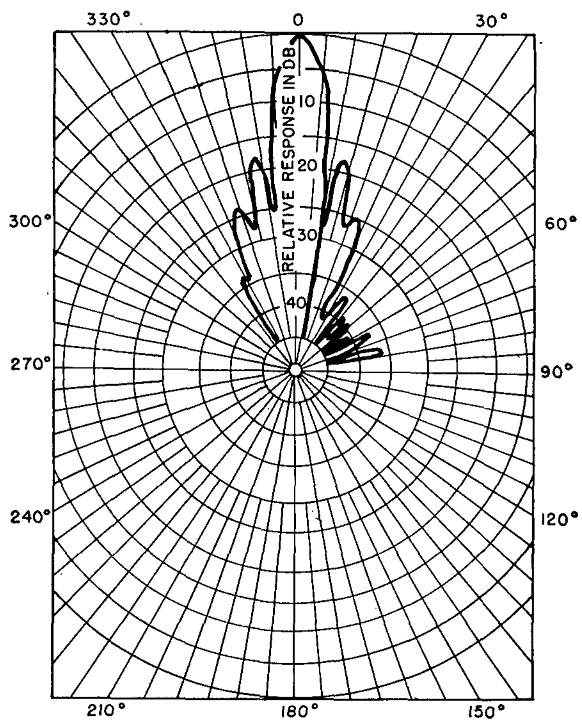


FIGURE 43. Directivity pattern for USDAR Model 500 (serial No. 1)—used as a projector at 495.6 kc.

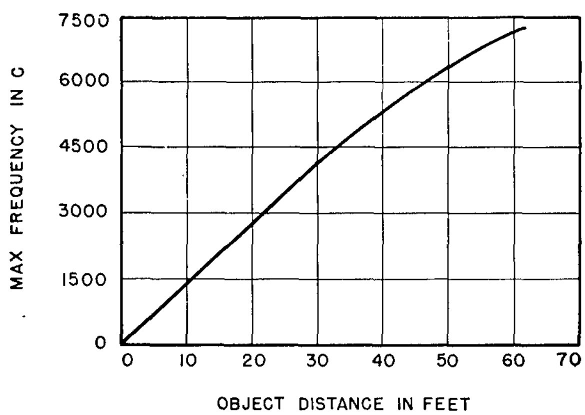


FIGURE 44. Relation between object distance and maximum frequency.

PERFORMANCE FIGURES

Figure 44 shows the calculated variation of the peak frequency of the output of the device with respect to distance. Tests conducted on two 500 A units showed a maximum range of approximately 190 ft. Other tests were made in the surf with two types of mines as targets. Satisfactory performance was obtained for target distances out to approximately 50 ft for water depths greater than about 2 ft. Attempts to work in shallower surf proved unsatisfactory, probably because of air and sand churned up in quite turbulent water.

In a series of tests performed by a demolition team, the following results were obtained:

1. Mines were detected at distances of 6 to 35 ft in clear water 2 to 5 ft deep.
2. One-foot diameter boulders were found at 10 ft, and larger rock masses were found at 40 ft in 4-ft deep clear water.
3. Water in which a great deal of sand was suspended cut the sensitivity against mines practically to zero.

Some mention should be made of the problem which presents itself when the object to be detected is a smooth plane surface. If the angle between the transmitted beam and the surface differs appreciably from 90 degrees, no echo will ordinarily be heard. However, immersion in water for any length of time will roughen

such a surface, and part of the outgoing signal, because of its short wavelength, will be returned as an echo.

Tables 1 and 2 give a summary of the results of tests on the USDAR 1000 (serial No. 2), USDAR 500 (serial No. 1), and USDAR 250 (serial No. 1) units. It will be noted from Table 1 that these three units have similar self-generated pressures and similar directivity indices. There is, however, a decided gain in the receiving response of the 500 unit over that of the 1000 unit, whereas the receiving response of the 250 unit is slightly higher than that of the 500 unit.

TABLE 1. Summary of calibration tests on RCA USDAR units.

Unit	Diameter of crystal (in inches)	Self-driven pressure at 10-ft distance—db vs 1 dyne per sq cm	Receiving response at peak—db vs 1 v	Audio response at 50 ft—db vs 1 v in series with crystal	Directivity index db	Calculated signal* Reflector at 50 ft—db vs 1 v
1000-2	½	81.4	−94.5	+3.9	−27.5	−52.2
500-1	1	80.3	−79.5	+7.0	−28.7	−35.2
250-1	2	81.6	−76.2	− .45	−28.2	−38.0

*For method of determining calculated signal, see bibliographical reference 3.

Table 2 summarizes the results of the field measurements on the three units. There is a large gain in the maximum distance reached with the 500 and 250 units over the distance reached with the 1000 unit. The audio-frequency voltage across the head receivers has been given for a 50-ft reflecting distance. It will be noted that these latter values agree closely with the calculated signals in Table 1 except for the 250 unit, for which the agreement is only fair.

TABLE 2. Summary of performance tests on RCA USDAR units.

Unit	Maximum range in ft	Noise voltage	Audio-frequency voltage across head receivers. Reflector at 50 ft—db vs 1 v
1000-2	70	.02	−51.0
500-1	120	.036	−36.2
250-1	150	.035	−33.8

8.15 RECOMMENDATIONS FOR FUTURE WORK

There should be a need for a device which fills the gap between USDAR and the standard ranging gear. The device would give qualitative information as to distance and direction and would probably be used on small naval craft in detection and location of medium sized obstacles. The immediate problems of such a device would be:

1. A new transducer to operate at a lower frequency and to have a broader directional pattern. The lower frequency would be necessary to reduce the doppler effect caused by the boat motion. The broader directivity is necessary to increase the field of the device.
2. Circuit development to give more range to the device, by way of more power. Compactness would not be so great a problem as with the present USDAR; therefore, new circuits using more and larger tubes could be developed.

The relative merits of pinging versus frequency-modulation systems for the above device should be investigated.

Some work has been done to convert the USDAR Model 500 A for use as a transmitting shallow water fathometer.[4] The principle is the use of a Wien Bridge in the circuit, by means of which the output frequency is determined. This in turn gives the distance to the target which in this case is the water bottom. Depths from 4 to 30 or 40 ft can be measured in this manner. Additional work is needed to improve and standardize this development.

Chapter 9

SECURE ECHO-SOUNDING EQUIPMENT

Secure Echo-Sounding Equipment

The secure echo-sounding equipment [SESE] is a small, low-power, echo-sounding equipment which was developed for submarine service. The primary design considerations were (1) accuracy at shallow depths and (2) "security" from overhearing. A range of depth measurement from 1 to 105 fathoms is provided. The feature of security is obtained by virtue of the high frequency employed (80 kc) together with minimum power output necessary to insure echo return. In operation, the keying interval is continuously varied by the operator, depending upon the water depth, until an echo is received just as the next signal transmission is made. The keying interval is, therefore, a measure of the water depth. As in some forms of radar, the controls are adjusted until the echo "pip" is lined up with a "marker" on the cathode-ray oscilloscope trace. Several secure echo-sounding equipment installations saw service in war patrols and satisfactory reports of this service were received. Development of secure echo-sounding equipment was carried on by the University of California, Division of War Research, San Diego, California.

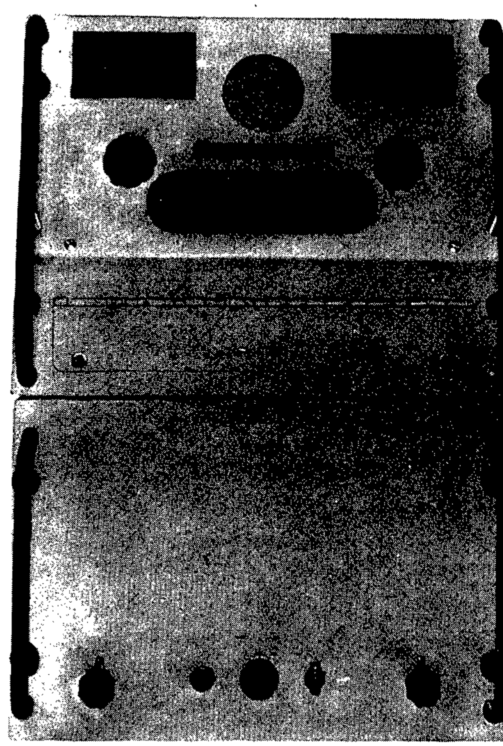


FIGURE 1. Control cabinet of SESE Model III-1.

9.1 INTRODUCTION

At the outbreak of World War II, the lack of a secure and accurate shallow water sounding device prevented the safe operation of submarines in many coastal waters frequented by enemy shipping. This was due, in part, to the hazard of running aground during evasive tactics when the submarines' echo-sounding equipment could not be used without revealing the location of the submarine. Even when the security considerations did not prevent the use of the echo-sounding equipment, the accuracy of the soundings in shallow water was not satisfactory.

Most U. S. submarines were equipped with sonar equipment which was, in general, comparable to the WCA-2 equipment. This equipment was very satisfactory for general navigation purposes but imposed a severe limitation on submarine application because (1) it did not provide dependable soundings at shallow depths, and (2) its operation could be readily detected by the enemy's echo-ranging and listening gear.

During the first two years of World War II, considerable work had been done on the regenerative object locator and the acoustic proximity fuse.[1] Each of these devices employs an amplifier and two transducers. The input is connected to one transducer and the output is connected to the other. They are so arranged that a target, when in the proper location, will reflect energy from the transmitting transducer to the receiving transducer, causing the system

to feed back and oscillate. It was suggested that such a system might be employed either as an "acoustic warning device" for submarines, by causing this oscillation to energize an alarm, or by modifying it for use as a secure sounding equipment.

An investigation of the general problem of secure sounding was started. The idea of adapting the regenerative object locator[2] to silent sounding was advanced by laboratory personnel. Since the regenerative object locator did not provide for range (depth) determination, a means of overcoming this deficiency was proposed.[3] The scheme involved the use of a regenerative sounding device, gated to operate at only a definite and limited depth range.

It was thought that the use of water-noise pings in such a device would increase security because listeners would be less suspicious of amplified water noise than of foreign sounds. After the ping echo was received and amplified, its energy was fed back into the output system, causing self-oscillation to be set up if the water depth corresponded to the gating interval. Use of the gated circuit was intended to offer additional security. A regenerative sounder was constructed but it was found that the echo signal could be detected on a cathode-ray oscilloscope [CRO] with greater security in shallow water (up to 100 ft) without the use of a self-oscillating circuit using aural indication. As a result of these findings, SESE was designed as a low-power echo sounder with a local oscillator.

SESE was installed on four submarines. Very favorable reports of these installations were returned from the field. However, SESE is not standard equipment on U. S. submarines because the NGA-type echo sounders, then in production by the Submarine Signal Company, were believed to be available in sufficient numbers to permit installation earlier than the best possible production date for SESE.

9.2 EXPERIMENTAL DEVELOPMENT

9.2.1 Design Considerations

The most important characteristics of a secure echo-sounding equipment for the submarine service were believed to be as follows.

Accuracy. The system should provide accuracy of approximately 5 per cent in depths ranging from 1 to 50 fathoms. The accuracy desired established the necessity for extremely short pulse lengths. If 4,800 fps is taken as the velocity of sound in water, then 2,400 fps is the effective "sounding" velocity. At a depth of 1 fathom, the travel time is 6/2400 or 2.5 msec. Therefore, the duration of the transmitted signal must be considerably less than 2.5 msec for good resolution. This short pulse length and the requirement for high accuracy demanded a highly developed control-indicator system. It was apparent that mechanical control of switching would be unsatisfactory, and that electronic means should be used. Similarly, an indicator system employing a CRO appeared desirable.

Security. The operation of the system must not be detectable by enemy observers at ranges greater than that at which the submarine's screws, pumps, etc., may be overheard when operating under evasion conditions (i.e., rigged for silent running). Basically, a low-power device was indicated. A high signal frequency, above the sonar frequencies known to be in use, was likewise desirable in order to avoid those bands normally covered by enemy listeners. These two requirements were in opposition, because at high frequencies the rate of attenuation of acoustic signals is also high. Studies of reverberation and other theoretical considerations suggested some advantage in the use of pulses of the order of 1 msec or less. The security requirement also influenced transducer design considerations, since a sharp beam was desirable in order to provide a good reflection efficiency and reduce scattering of the output energy.

Small Size. The entire electronic equipment should be small in order to facilitate installation in the submarine. In addition, it was desirable that the central equipment be small to permit installation in the conning tower.

Simplicity. The system should be simple to operate and the indication should be easily interpreted. The requirements for simplicity and small size could obviously be fulfilled only after a design had been reached which first satisfied the requirements for accuracy and security.

9.2.2 Proposed Sounding Systems

In these experiments, 80 kc was chosen for the operating frequency as being well above the probable range of enemy listening gear. This frequency was also low enough for reasonable crystal transducer design. The sharply tuned filters in the amplifiers were designed to accept only those frequencies lying between 76 and 84 kc.

Gated Acoustic Feedback System

In this system, the circuit was gated at a controlled rate. The pulse rate was adjusted so that a pulse was sent out just as the echo from the previous pulse was being received. If the overall gain of the loop, including the water path, was sufficiently high, the circuit would build up by acoustic feedback and oscillate. The oscillation would occur at supersonic frequencies and could be made audible by a heterodyne detector employing a beat-frequency oscillator.

The circuit tested in breadboard form is indicated in the block diagram of Figure 2. When the circuit was adjusted to obtain acoustic feedback, a beat note was audible in the telephone receivers. This beat note indicated that the gating interval was equal to the pulse travel time. The dial of the gating-interval control was calibrated in fathoms.

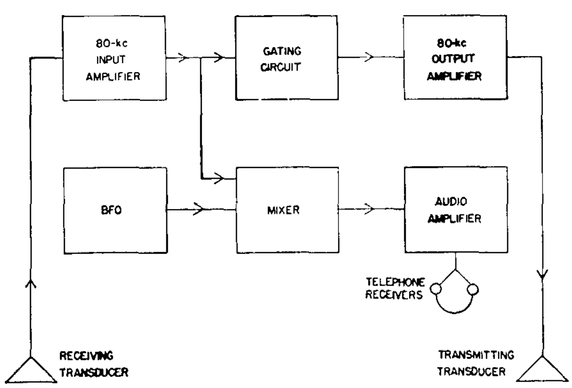


FIGURE 2. Block diagram of gated feedback sounding system.

Gated Water-Noise System

During the investigation of the acoustic feedback system, an oscilloscope, which was being used for monitoring, revealed that echo pulses were detectable even at times when the gain of the circuit was insufficient to produce build-up and oscillation. Under this condition, it was still possible to adjust the gating interval to obtain coincidence of pulse and echo while observing the CRO screen. The circuit was the same as the one previously used, but operation was possible at a much lower power level. Since security was of paramount importance, it was apparent that the gated water-noise type of operation had a substantial advantage over the feedback method of operation. At the same time, the advantage of the CRO as an indicator had been demonstrated.

Local Oscillator System

It was believed that the spectrum of the water noise signal, after having passed through the filter and gating circuits, would not be greatly different from that of a locally generated signal. Accordingly, the local oscillator circuit shown in Figure 3 was set up in breadboard form and tested. Tests[4] showed that the gated water-noise pulse closely resembled that of the local oscillator. The use of a local oscillator did not impair the security of the system, and offered the advantage of constant output level,

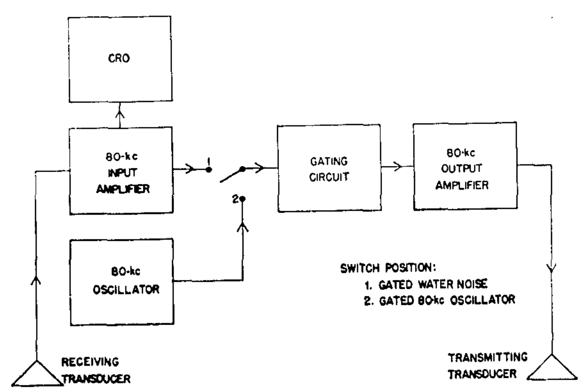


FIGURE 3. Block diagram of gated water noise and gated oscillator sounding systems.

whereas the amplitude of the water-noise signal varied with the ship's speed and location.

9.2.3 Evaluation of Proposed Systems

The sounding equipment, assembled from the circuit of Figure 3, was tested in a small boat and aboard a submarine, using crystal transducers. Dock, bay tests, and sea trials were conducted during which all three modes of operation were tested and overhearing tests made. The following was observed.

1. The acoustic feedback system did not function at sufficient depths and the signals were overheard at ranges up to 200 yd.
2. The water noise and local oscillator systems were superior both on the basis of the soundings obtained and also in connection with the security which was afforded.

9.2.4 Conclusions

It was decided to proceed with the construction of a more compact sounding equipment which would be capable of operation either from water noise or from a local oscillator. Both methods were to be used since it was still uncertain as to which system offered the greatest security.

At the same time, an investigation was undertaken to determine which system was the most difficult to overhear.[4] Preliminary tests, later verified by this invesigation, indicated that for equally short pulses there would be little or no difference in the overhearing possibilities of the two systems through water noise.

9.3 SECURE ECHO-SOUNDING EQUIPMENT MODEL I

DESCRIPTION

The SESE Model I, Serial No. 1404 was the first complete sounding device constructed and provided means for either water noise or local oscillator pings. All the electronic equipment was included in a steel cabinet measuring approximately $27 \times 14 \times 13$ in. and weighing about 160 lb (Figure 4). The cabinet contained three chassis: (1) receiver amplifier, (2) output amplifier and power supply, and (3) CRO chassis and power supply. The type 3FP7

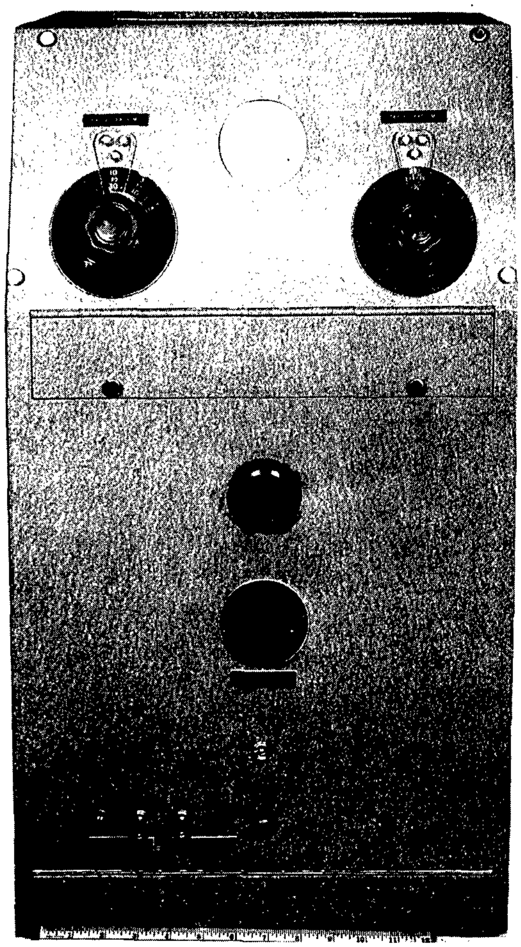


FIGURE 4. Front view of SESE Model I control cabinet.

cathode-ray oscilloscope [CRO] tube which has a long-persistence screen was employed in the indicator circuit. The range-fathoms dial of the indicator was calibrated in four scale ranges: 1—3, 3—10, 10—30, 30—100 fathoms.

OPERATION

The block diagram shown in Figure 5 illustrates the circuit arrangement. The positive-bias multivibrator initiates the sweep gener-

ator. The output of the sweep generator is amplified by the vertical amplifier and presented to the y-axis deflection terminals of the CRO. The multivibrator also supplies a pulse, delayed 180 degrees with respect to the sweep-initiating pulse, to the trigger circuit. The

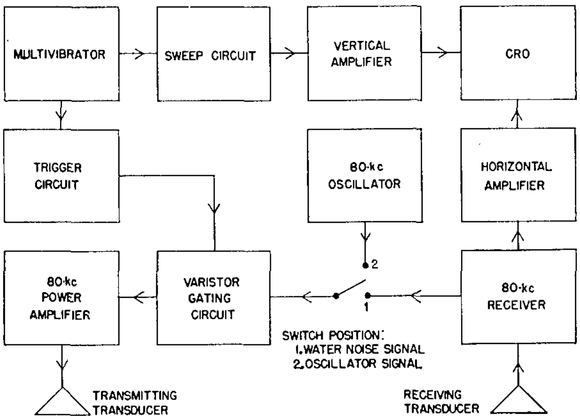


FIGURE 5. Block diagram of SESE Model I.

trigger circuit controls the varistor gate circuit (connected as a ring modulator), permitting a pulse of signal voltage to pass to the power amplifier. Therefore, a ping, delayed 180 degrees with respect to the sweep, is transmitted downward from the transmitting transducer when the trigger circuit is operated. This outgoing ping produces an x-axis deflection at the center of the CRO sweep and serves as a marker on the trace (Figure 6). The duration of this

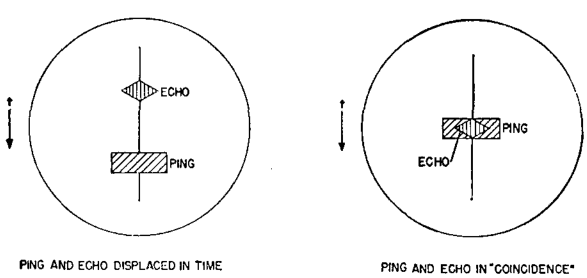


FIGURE 6. CRO indicator for Model I SESE.

ping is controlled by the RC constants of the trigger circuit, as determined by the depth scale being used. The interval between pulses depends on the multivibrator frequency which is adjusted to the depth being measured. Since the equipment is calibrated from 1 to 100 fathoms, the multivibrator (time base) operates over the range of 400 to 1 cycles per second.

The echo of the transmitted pulse is picked up by the receiving transducer and amplified by the receiving amplifier. The receiver output is further amplified by the horizontal amplifier and presented to the CRO as x-axis deflecting voltage. If the ping rate has been adjusted to correspond with the water depth, then the travel time of the pulse is just equal to the interval between pulses. When this adjustment has been made, the echo of one pulse will be received just as the next succeeding pulse is being transmitted. The echo deflection on the CRO will then coincide with the deflection caused by the ping (Figure 6). Until this adjustment has been made, the echo will appear at some other point on the trace.

It should be noted that two different methods of operation are provided, depending upon the position of the selector switch. In position 1, the output of the receiver is connected to the input of the gate circuit; in position 2, the output of the oscillator is connected to the gate circuit. The essential difference between these pinging methods lies in the character of the high-frequency signal source.

For maximum security in operation, the power-amplifier gain control should always be set at the lowest value at which the echo deflection is adequate for observation above the ambient water noise. The maximum power which can be fed into the transducer circuit is approximately 10 watts. A small fraction of this power is converted into acoustical energy by the transducer.

TRANSDUCERS

After several transducers had been constructed and tested, the GD16 transducer was finally selected as having the best directivity and efficiency for the purpose. These transducers consist of an array of 128, 45-degree, Y-cut Rochelle salt crystals, measuring 1.0 x 0.090 x 0.320 in. (Figure 7). The crystals are glued to a vitreous-enameled steel backing plate, 4 in. square. This crystal motor is housed in a cast Meehanite case from which it is insulated acoustically and electrically by a

Corprene case lining. A neoprene diaphragm seals the front of the case and the interior is filled with castor oil, introduced under vacuum.

When operating at 80 kc, the main lobe of the transducer's directivity pattern was aproximately 15 degrees wide, 6 db down from the maximum. The first side lobes are about 15 db lower than the main lobe. The impedance at

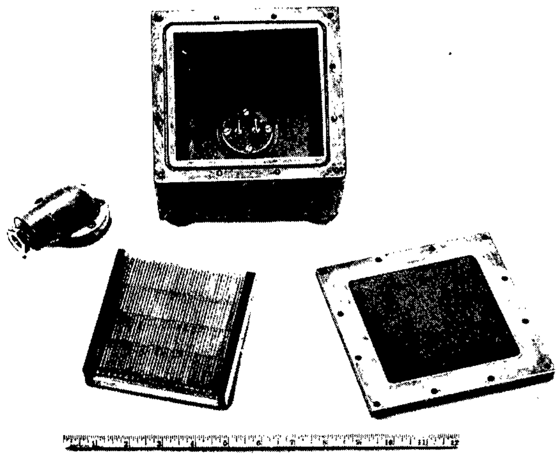


FIGURE 7. Disassembled view of UCDWR-type GD16 transducer.

this frequency is $60 - J1350$ ohms. Thus, with the transmission lines loaded with a series inductance of 2.68×10^{-3} henry, the load appears as approximately 60 ohms, resistive. The low line impedance makes possible efficient coupling between the transducers and the electronic equipment. The GD16's were used both in the transmitting and receiving positions.

9.3.1 Evaluation

Based on the results of experience gained in the experimental installation aboard submarine and surface craft, and the results of overhearing tests,[5] which had been made about the same time, the following conclusions were reached regarding the performance of the SESE Model I equipment.

1. The security of SESE Model I was insured by the use of high frequency, short pulse length, and low power. The 80-kc frequency was particularly advantageous since it was above the frequency bands known to be in use by enemy sonar equipment and also provided a high rate of attenuation of undesired leakage radiation. Such leakage or scattering was of small magnitude because of the favorable beam patterns of the GD16 transducers at 80 kc.

2. The performance of SESE Model I, using either the water noise or local oscillator mode of operation, had been proved satisfactory, both with respect to operation at shallow depths and also over a wide range of bottom conditions, including mud, at 60 fathoms. It was believed that a streamlined transducer mounting would permit operation at speeds greater than the 10 knots used.

3. The convenience of SESE operation could be improved by housing the electronic equipment in a cabinet small enough to permit mounting in the conning tower of the submarine.

4. Greater convenience in operation could also be achieved by means of an improved dial design. The improvements suggested were that the calibration be made linear with respect to time or depth, rather than the frequency, and that a slide-rule type of dial with only one scale visible at a time, replace the disk-type dial used on Model I.

9.4 SECURE ECHO-SOUNDING EQUIPMENT MODEL II

9.4.1 Design Changes

ELECTRONIC

The principal electronic improvements incorporated in the design of Model II SESE (serial No. 1405) were as follows.

1. Replacement of the varistor gate circuit by a vacuum tube keying circuit. The varistor gate previously used in Model I provided only about 40 db attenuation of the oscillator signal during the interval between pulses. This was not enough to remove all the steady 80-kc signal on the x-axis of the CRO. This residual 80-kc signal from the oscillator resulted in a blurring of the CRO trace, and made detection of weak signals difficult. The new vacuum tube circuit

employed a keying tube in the oscillator cathode circuit. The bias on the keying tube was such that the oscillator remained blocked during the interval between pings. This prevented any leakage signal from broadening the CRO trace. It also permitted higher gain in the receiver, which reduced the demand for output power. Thus, the security of the system was improved.

2. Elimination of the gated water-noise type of operation simplified the design problem generally, and also the operating technique. Experiments on the masking effect of water noise on short pulses[4] and the overhearing tests[5] had established the fact that a gated water-noise signal offered no advantage over the single frequency of a local oscillator.

3. A new push-pull 80-kc oscillator which increased the frequency stability of the system and provided a greater output voltage, thereby reducing the number of stages required in the power amplifier. This push-pull oscillator proved ideal for control by the keying system.

4. A step-type marker circuit for the CRO which made possible a greatly improved CRO presentation. The "leakage" signal from the outgoing ping was no longer needed for a "time" marker on the trace. The new step-type marker was developed by introducing a partially filtered voltage sample of the keying pulse, into the x-axis deflection circuit. The echo pip on the CRO trace is easily fitted into the step, as shown in Figure 8.

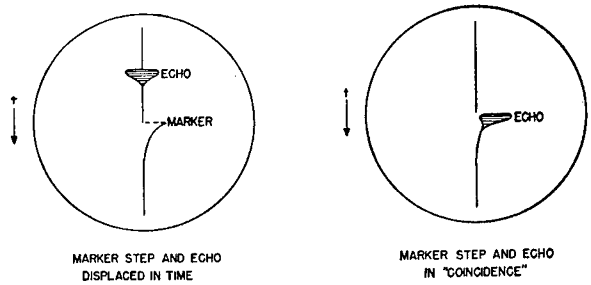


FIGURE 8. CRO indicator for Model II SESE.

5. The CRO tube was rotated 90 degrees, thereby interchanging the x- and y-axes. This resulted in a vertical sweep trace in which the electron beam moved downward rather than from left to right, and made it possible to observe the image from some distance either to the right or left of the SESE cabinet. The downward sweep was also suggestive of the depth-sounding function of SESE.

Mechanical

A number of mechanical improvements were made in the SESE Model II. The principal changes included a smaller and lighter weight cabinet, a new slide rule, and an edge-lighted dial which showed only one of the four scales at a time. The dial minimized confusion in reading by concealing the three scales which were not in use. This dial, which was designed for conning tower installation, also minimized the leakage of light from the dial. These features fulfilled the naval requirement for lighting of conning tower installations.

Remote Indicator

In order to provide for remote reading of the SESE depth indication, a remote indicator circuit was designed and an experimental model built. The device consisted essentially of a potentiometer mounted in the SESE control cabinet and connected to the dial potentiometer. An extra "deck" added to the range switch in the Model II equipment served to switch scales in the remote indicator. A milliammeter served as an indicator at the remote location, and its reading thus depended upon the position of the range and dial knobs of the SESE. The meter was calibrated 0-100 fathoms in logarithmic fashion. The remote indicator was energized from the SESE regulated power supply, and the selector switch varied the voltage applied to the potentiometer in accordance with the scale used. Thus, the depth in fathoms was clearly shown on the remote indicator regardless of the depth being measured. It should be noted that proper operation of the remote indicator depended upon the operator's matching the echo with the marker. Although no provision was included in the experimental model, it would be a simple matter to provide a pilot light or some other form of indicator which would indicate that the SESE was on target. This equipment operated satisfactorily but was not included in any of the submarine installations subsequently made.

9.4.2 Tests

SESE Model II was installed in the control room of a submarine for operational and overhearing tests. The transducer assembly, set in a sea chest welded to the keel, was located approximately 3 ft above the keel on the port side.

Overhearing Tests

An extensive program of overhearing tests[5] were made in order to check the security of the system. During these tests, it was found that the maximum distance at which the operation of SESE Model II could be detected was as follows.

1. On its operating frequency of 80 kc, a heterodyne receiving system could not detect the 80-kc signals at ranges greater than 300 yd. There was no indication of the signal at any range on the sonic or 24-kc supersonic bands. These results were considered very favorable since the self-noise of a submarine was audible at a distance of 450 yd in the 80-kc band, 500 yd in the 24-kc band, and over 500 yd in the sonic band. These tests were made at a 3-knot submerged speed.
2. The submarine's type WCA-1 fathometer was heard at a distance of 1,500 yd. At this distance, the strength of the signals indicated that it might easily have been overheard at several times this range, but no tests were made at ranges of greater than 1,500 yd. It was concluded from these tests that the use of the secure echo-sounding equipment does not hazard the safety of a fleet-type submarine.

Operational Tests

Performance tests of SESE Model II over various known bottom conditions in the vicinity of San Diego provided reliable soundings up to 100 fathoms at surface speeds as high as 12 knots. On one occasion, a depth of over 300 fathoms was measured by use of the multiple-transmission formula given in Section 9.5.4. Soundings were difficult to obtain at speeds greater than 12 knots because of turbulence in the water around the transducer which often blanked out reception of the returning echoes. However, in water less than 25 fathoms deep, good soundings were obtained at speeds up to 16 knots.

During tests conducted at Pearl Harbor, good results were obtained over rough coral bottoms in depths as great as 80 fathoms at a surface speed of 6 knots. At a 10-knot surface speed, depths up to 50 fathoms could be measured. The limitation with respect to speed was apparently due to improper fairing of the transducer.

9.5 SECURE ECHO-SOUNDING EQUIPMENT MODEL III

Previously, only the general characteristics of subsequent SESE developments have been described. In this section, a detailed description will be given of SESE Model III-3, similar to two previous Model III equipments, but provided with an improved marker circuit and a calibration circuit.

9.5.1 Design Changes

The experience gained with SESE Model II indicated that a number of minor modifications were desirable. The principal changes in Model III were as follows.

1. The electronic cabinet was redesigned. The new construction provided for a cabinet containing two sliding-drawer type chassis. Provision was made for operation of the chassis when removed from the cabinet by means of patch cords which were supplied with the equipment.
2. The dial calibration was changed slightly in order to indicate depth of water under the keel, rather than depth below the transducer, as in previous models. Models I and II had been calibrated from 1 to 100 fathoms without any scale overlap. Model III had essentially the same calibration except that a 1-fathom correction for "depth under keel" was made, and the scale was calibrated in four steps as follows: 0 to 3.5, 3.0 to 10.5, 10 to 35, and 30 to 105.
3. The transducer was relocated. In the SESE Model II installation, the transducer had

been mounted some distance above the keel in the center part of the submarine. At the new location, the transducer was approximately 6 ft above the keel line and 16 ft from the bow. As the location was well forward, the probability of detecting shoaling conditions before the bow of the boat grounded was greatly increased. This effect was accentuated by a slight tilting of the transducer so that it had a forward angle of 5 degrees. By these two devices, the sounding equipment, to some extent, "anticipated" changes in depth.

9.5.2 Details of Construction

The Model III SESE consists of two major items: a control cabinet which contains all the electronic components and the transducer assembly (Figure 9) which is mounted in the keel

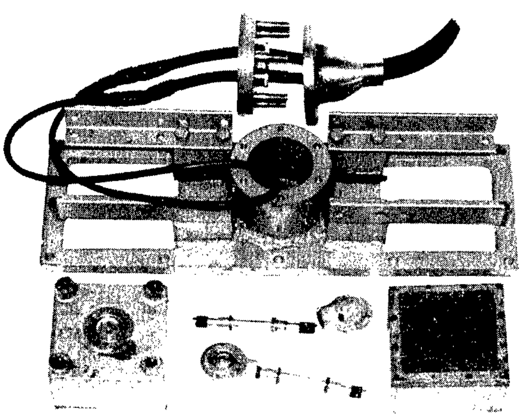


FIGURE 9. Disassembled view of UCDWR-type FH dual transducer assembly with two type GD16 transducers.

of the submarine. The necessary connecting cables and loading coils constitute the balance of the installation. It should be noted that in two of the Model III installations, the cabinet was not installed in the conning tower, but was installed in the control room. However, the cabinet was designed for installation in the conning tower and this location is believed preferable to the control room. The equipment is operated from the 120-v, 60-c a-c supply and requires approximately 300 w.

CONTROL CABINET

The upper chassis (Figure 10), referred to as the CRO chassis, contains the CRO, the range and dial controls, and the slide rule indi-

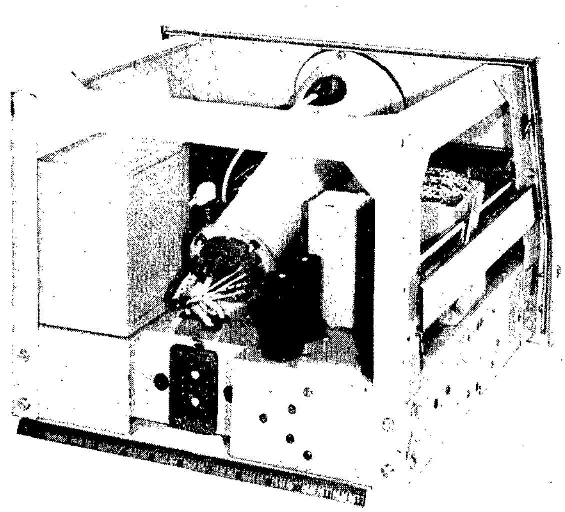


FIGURE 10. Upper chassis of SESE Model III.

cator scale. The CRO controls are located behind the hinged door at the bottom of the CRO chassis panel. In addition to the CRO and its power supply, the multivibrator, sweep circuit,

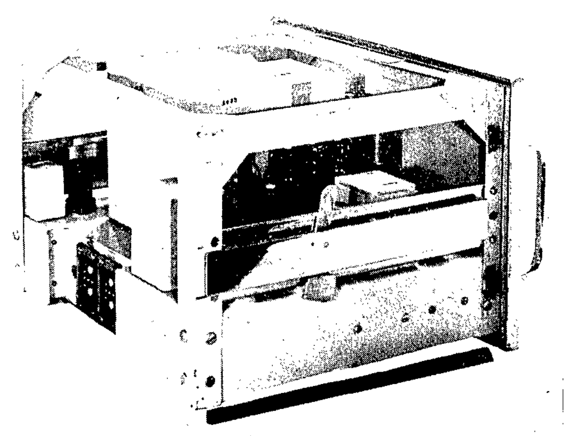


FIGURE 11. Lower chassis of SESE Model III.

horizontal and vertical amplifiers, trigger circuit, and marker circuit are all installed in the CRO chassis.

The lower chassis (Figure 11) contains the

oscillator, power amplifier, receiver, and the regulated power supply. The latter furnishes all power except that used by the CRO. The output control knob is located at the lower left of the panel, and the receiver sensitivity control knob is located at the lower right. Between them are located the power switch, the pilot light, and the power fuse.

TRANSDUCER ASSEMBLY

The type FH transducer unit (Figure 9) includes two identical UCDWR-type GD16 transducers, which are shown in Figure 7. In addition to the transducers, the FH unit includes a connection box, stuffing tubes, and other accessories which are required for a watertight interconnection system. Either of the two GD16 transducers may be used for transmitting or receiving but the forward unit is usually connected to the transmitter. Spares are provided in case of damage to either unit. The installation or repair of the transducer is the only operation which involves dry-docking the boat. In order to protect the transducer connecting cables a copper-pipe conduit, capable of withstanding full water pressure, is run from the connection box at the center of the unit through the inner hull of the boat. Stuffing boxes are provided to prevent water from entering either the transducers or the inner hull in the event of damage. The transducer system is tuned to 80 kc by means of series-connected toroidal inductors which are mounted in a junction box at the point where the conduit enters the inner hull.

9.5.3 Operation

The principal units are shown in the block diagram, Figure 12. The wave forms encountered in the various circuits are depicted within the block-enclosed circles. The time t represents the period $1/f$ as determined by the multivibrator frequency at any particular setting of the depth dial. All the events portrayed occur during this time. A CRO is used to indicate both the instant of keying and of the receipt of the echo. Adjustment of a pointer on a calibrated depth scale apparently moves the echo signal "pip" to correspond with a "marker" signal, as in certain types of radar equipment. Actually, this adjustment changes the interval between transmissions or pings. Thus the ping rate is adjusted so that the echo of one ping is received just as the next ping is transmitted. The depth in fathoms is then read directly from a calibrated scale.

Operation is initiated by the multivibrator which sends a pulse to the trigger circuit, which in turn keys the 80-kc oscillator. The duration of the pulse or ping is a function of the RC elements in the trigger circuit. The 80-kc signal is then amplified by the power amplifier and fed to the output transducer, creating an energy pulse in the water. This pulse is projected downward and reflected from the bottom as an echo, which is picked up by the receiving transducer. The voltage thus developed across the receiving transducer is amplified by the receiver amplifier and fed to the x-axis deflecting electrodes of the CRO through the horizontal amplifier. This places an echo signal pip on the CRO.

The sweep of the CRO is synchronized with the keyed pulses initiated by the multivibrator. For this reason, the position of both the marker and the pip appear stationary on the CRO screen. The frequency of the multivibrator is adjusted by the operator until the echo pip and the marker coincide on the CRO screen. Under this condition, an echo is being received at the same instant that the next transmission is started. The frequency of the multivibrator is then an exact indication of the depth of the water, since the time between pulses is then the time required for one pulse to be transmitted to the bottom and to be returned as an echo.

The rate at which the transmitter is keyed and the sweep rate of the CRO are adjustable simultaneously by means of the dial and range controls, which govern the frequency of the multivibrator.

The other principal controls are the power amplifier gain control (output) and the receiver-amplifier gain control (sensitivity). The output control regulates the power radiated into the water, and the sensitivity control regulates the amplification of the echo signal in the receiver.

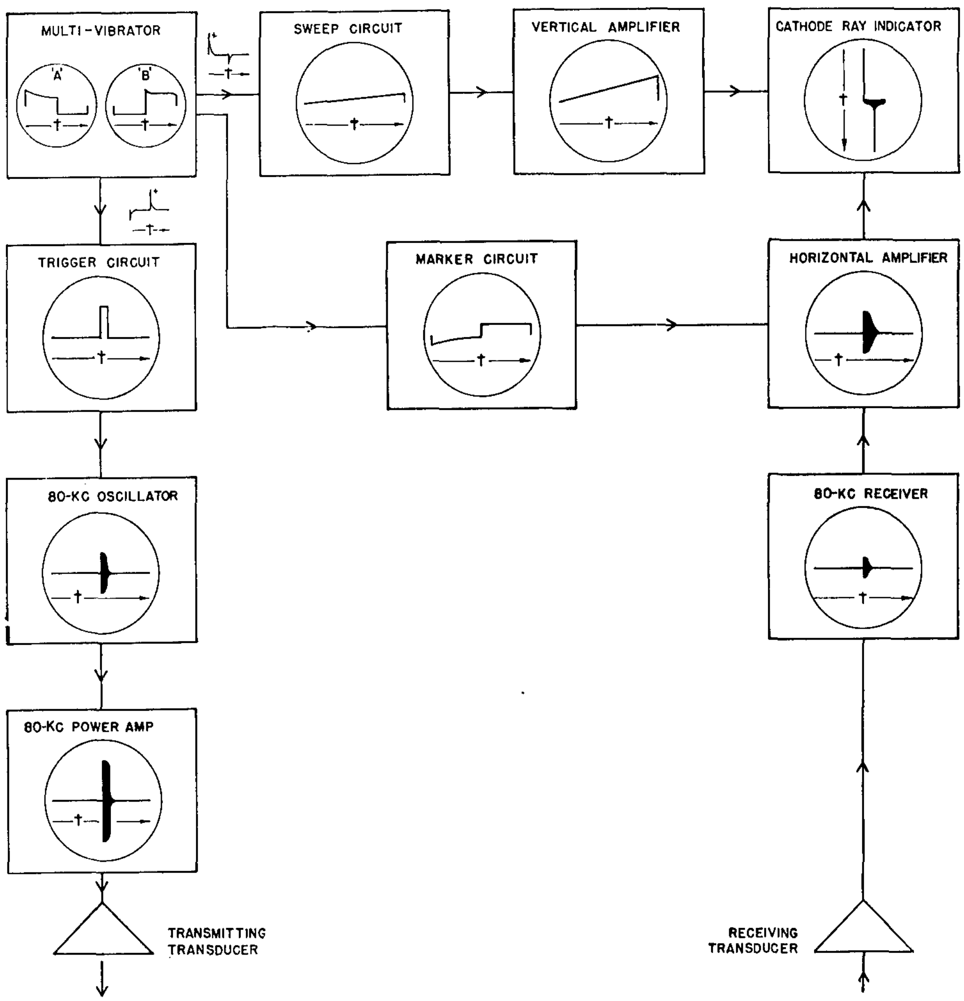


FIGURE 12. Block diagram of SESE Model II and Model III.

Both controls, therefore, have an effect on the amplitude of the pip on the CRO screen. The power switch is used to turn the equipment on and off.

9.5.4 Theoretical Limitations

Coincidence of echo pip with the marker may occur for other than true depth settings. All that is required to establish coincidence is that a signal be sent out just as an echo is received. The true depth will be indicated only when the echo from one ping is received at the exact instant that the next ping is transmitted. Under these conditions the period of the multivibrator frequency is exactly equal to the travel time to the bottom and return. Thus, the dial calibration for a depth of 10 fathoms represents a multivibrator frequency of 40 c. Now if the dial is set up to 50 fathoms in water 100 fathoms deep, then two pings are in transit at the same time. The echo from the first ping will be received just as the third ping is being sent out and coincidence will be observed on the CRO. Similar indication will occur at settings of $\frac{1}{3}$, $\frac{1}{4}$, and $\frac{1}{5}$ of the true depth and this is referred to as "the multiple-transmission effect." If the deeper range scales are first investigated by the operator, and a check is always made to determine the maximum depth at which coincidence can be obtained, no error will occur, because no coincidence of echo pip and marker is possible with dial settings greater than the true depth.

MULTIPLE-TRANSMISSION EFFECT

Under favorable conditions, soundings are possible in water deeper than 104 fathoms. Jagged rocks and coral formations are less favorable to deeper soundings than smooth rock or sand bottoms. The following formula is based upon the multiple-transmission effect and may be used to measure depths greater than 104 fathoms.

$$D = \frac{d_1 d_2}{d_1 - d_2},$$

where d_1 equals the greatest dial reading at which the echo and marker will coincide and d_2 equals the next lower reading at which coincidence may be obtained.[a]

9.5.5 Details of Electronic Circuits

The electronic circuits will be described on the basis of their function as indicated on the block diagram, Figure 12. The schematic wiring diagram of Figure 13 will reveal the details of the entire system. The relative action of the circuit parts with respect to time is shown in Figure 14.

MULTIVIBRATOR

The multivibrator which is the "heart" of SESE employs a twin triode 6SL7 (V-101). It consists of a two-stage resistance-coupled amplifier in which the output of each stage is coupled to the input of the other, thus forming a relaxation oscillator which functions as a switch, causing one triode to conduct while the other is cut off. Then it flips over so that the conditions of cutoff and conduction are interchanged between the two halves of the tube. At each flip-over, the grid of one triode is driven negative to cutoff. The grid condenser discharges through the grid resistor until the triode is again in an amplifying condition. At this point, the rising potential applied to the grid is amplified in the plate circuit and drives the grid of the other triode to cutoff. The rate at which these flip-overs occur may be controlled by changing the RC constants of the grid-plate components, or by changing the positive bias on the grids. The use of both methods is indicated below.

1. The RC constants of the grid-plate circuit of both triodes are simultaneously changed by the range control which switches different values of condensers, C-102 and C-103, into the circuit in order to give four ranges, indicated in Table 1.

2. The positive bias of the grids is varied by the dial potentiometer (R-101) as well as by the calibration control dual potentiometer (R-110). A calibration adjustment is provided by the potentiometer (R-102) which is in series with the dial potentiometer (R-101). This control is a potentiometer with a screwdriver adjustment. The variable resistor (R-102) is used to adjust the calibration at the low end of the depth scale; the dual potentiometer (R-110) is used to adjust the calibration at the high end.

The multivibrator thus produces a square wave which appears at the cathodes of the *A* and *B* sections of V-101 with a 180-degree

TABLE 1. Multivibrator calibration.

Range	Grid condenser section A		Capacity section B		Frequency range of multivibrator	Depth* in fathoms, below transducers
A	C-102A	0.002	C-103A	0.002	400 to 114.3	1.0 to 3.5
B	C-102B	0.006	C-103B	0.006	133.3 to 38.1	3.0 to 10.5
C	C-102C	0.02	C-103C	0.02	40.0 to 11.4	10.0 to 35.0
D	C-102D	0.06	C-103D	0.06	12.9 to 3.8	30.0 to 105.0

*The depth shown in the table is not the calibration depth, which is uniformly 1 fathom less than the value shown.

[a] This formula is exact when the values for D and d are measured from the transducer. The maximum error introduced by the use of this formula, when the fathom correction for height of the transducers above the keel has been made on the scale, is of the order of 3 to 5 per cent.

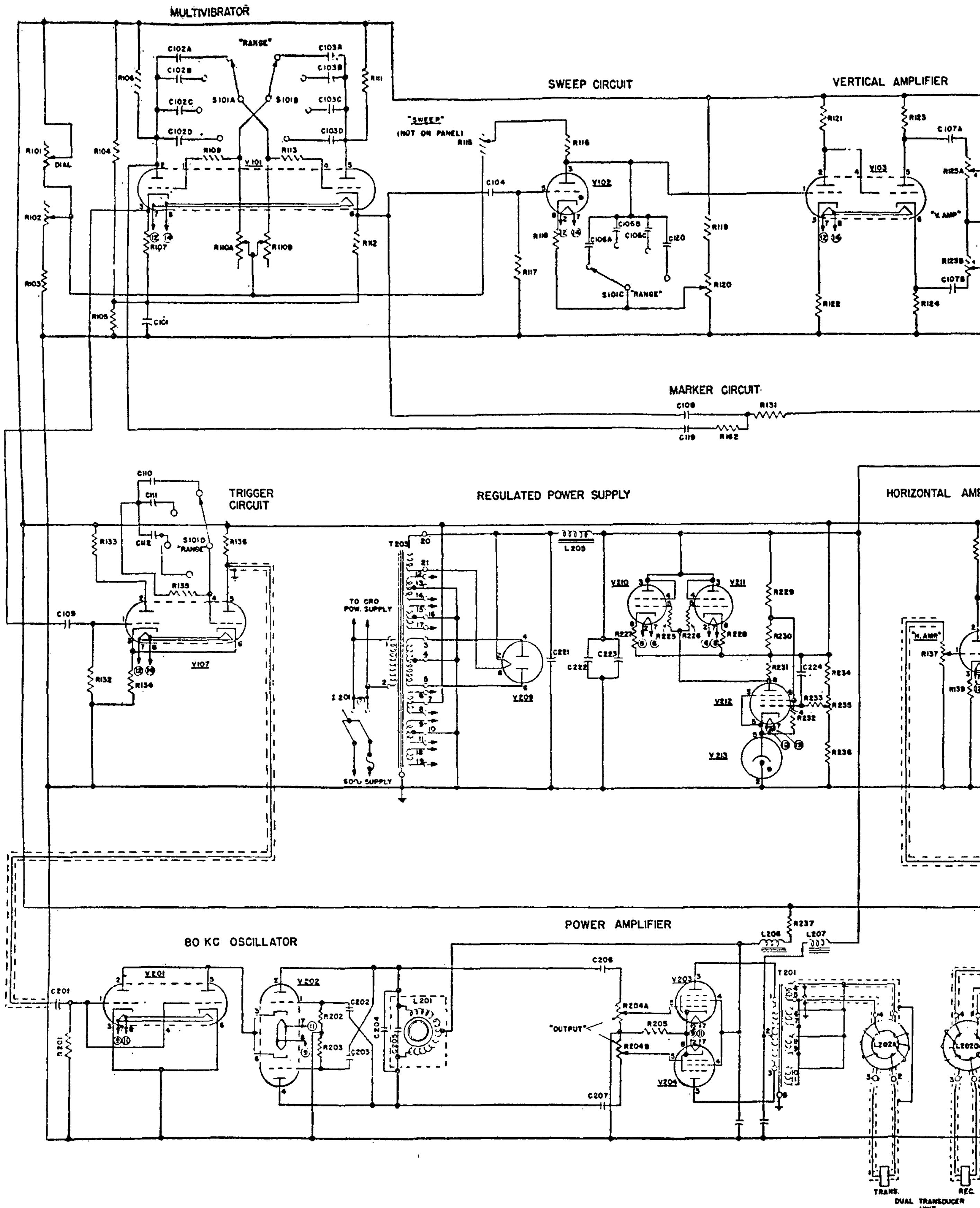


FIGURE 13. Schematic wiring diagram of SESE M

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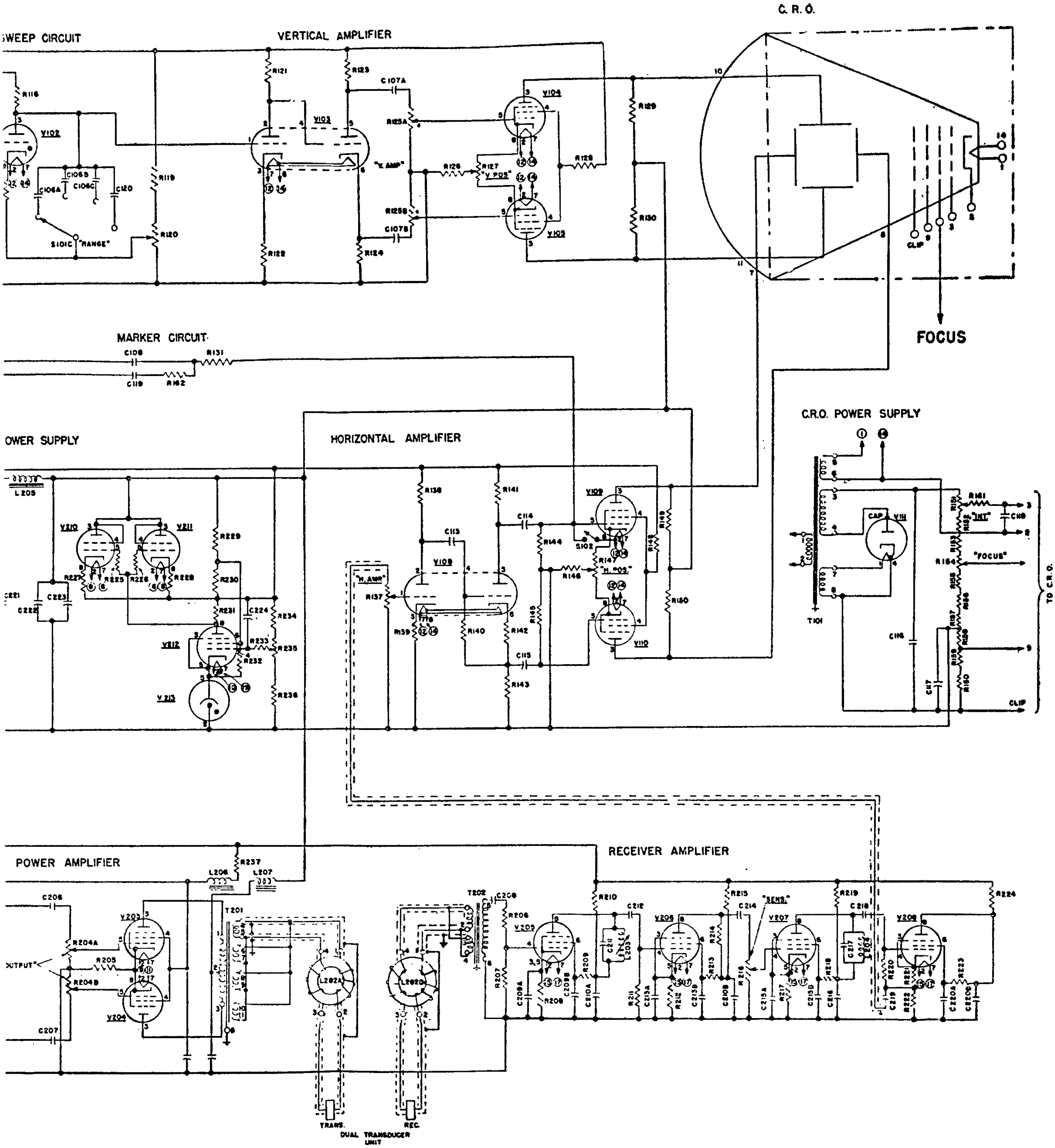

FIGURE 13. Schematic wiring diagram of SESE Model III.

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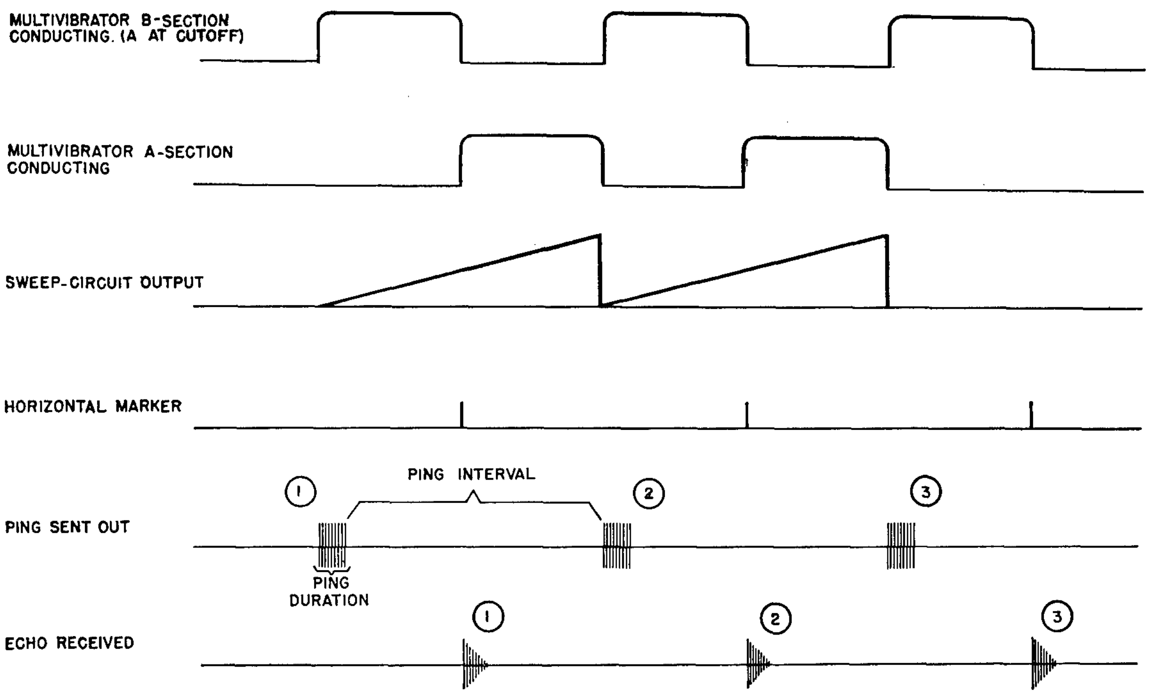


FIGURE 14. Sequence of circuit action with respect to time.

phase (time) difference, as shown in Figure 12. The *A* section excites the trigger (pulse generator) through the differentiating circuit C-109 and R-132. The sweep generator is initiated by the *B* section through a similar network C-104 and R-117, thus synchronizing the sweep with the multivibrator. These differentiated pulses are shown in Figure 12. The marker step is placed on the sweep trace of the CRO by feeding the square wave output of the multivibrator into the horizontal amplifier. This is accomplished by the coupling network C-108, C-119, R-162, R-131.

As the positive pulses (half waves) from the multivibrator cathodes are 180 degrees apart in phase, the sweep on the CRO has completed half its journey across the screen when the associated ping is transmitted. This coincides with the marker in the trace which is developed by the negative half cycle appearing at the *B* section of the multivibrator at the same instant the *A* section goes positive to initiate transmission.

MARKER CIRCUIT

The marker circuit is used to produce a step on the CRO trace which indicates the instant of the transmission of the signal. This is accomplished by a circuit which forms a connecting link between the multivibrator and the horizontal amplifier which is feeding the CRO. The output of the multivibrator, as seen at either cathode of V-101, does not produce a neat, square, step marker on the CRO trace. Therefore, the voltage appearing at the *B* section cathode, which is fed through condenser C-118, is supplemented with the voltage from the *A* section plate. This voltage, which is in phase with the voltage from the *B* section cathode, is fed through condenser C-119 and resistor R-162. These voltages are added and passed through resistor R-131 to the horizontal amplifier. Since the horizontal gain control (R-137) is in the first stage of the horizontal amplifier, it has no effect upon the amplitude of the marker deflection.

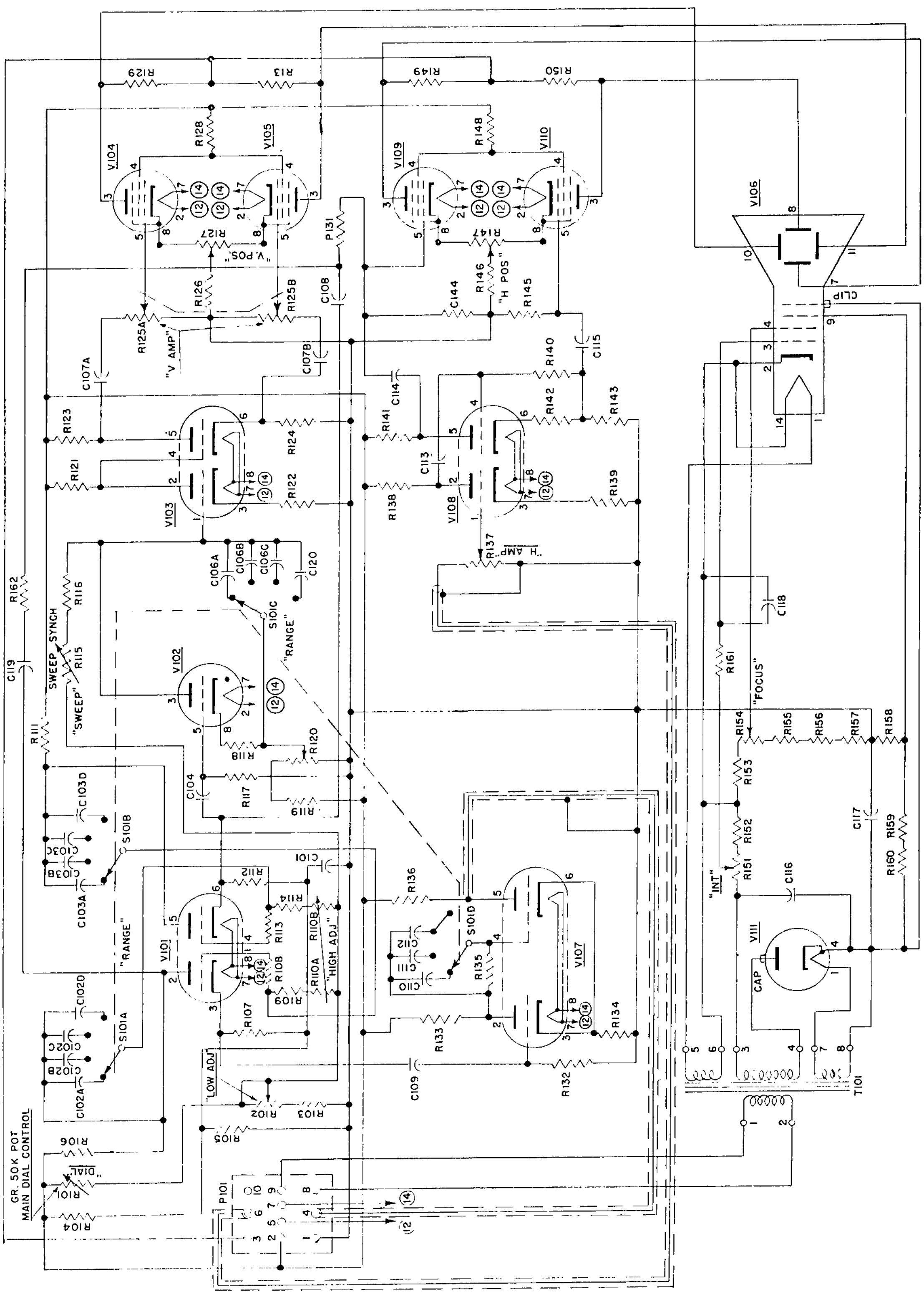


FIGURE 15. CRO chassis wiring diagram for SESE Model III.

Sweep Circuit

The sawtooth sweep voltage is generated by the action of V-102, an 884 gas tube, and is fed to the input terminals of the vertical amplifier. The grid of the gas tube is connected to the cathode resistor, R-112, from which it receives the timing pulse. The plate and cathode of the gas tube are connected through condenser C-106A, C-106B, C-106C or C-120, depending upon the setting of the multivibrator control switch, to which the condenser selector switch is ganged. The condenser is thus charged by the same variable voltage supply which feeds the grids of the multivibrator. The voltage output of the sweep circuit, therefore, rises at linear rate as the condenser C-106 or C-120 charges, until the ionization point of the gas tube is reached causing the tube to conduct. The condenser then is rapidly discharged. This generates the sawtooth wave which, when amplified by the vertical amplifier, produces the sweep deflection voltage.

The natural frequency of the sweep circuit is controlled by the sweep circuit variable plate resistor, R-115. If this resistance is too low in value, the sweep condenser will charge sufficiently to cause the gas tube to fire before the keying pulse is received from the multivibrator. Thus, the sweep will lose synchronism with the multivibrator, and the marker and echo will no longer appear stationary on the oscilloscope, but will jump about in an erratic manner. If the resistance is too high, the amplitude of the sweep will be diminished. Since the potentiometer should rarely require adjustment after once being set, it is not brought out to the front panel.

Vertical Amplifier

The vertical amplifier consists of a twin triode preamplifier and inverter (6SN7) followed by a push-pull stage (two 6V6 beam power tubes). The sweep signal is fed into the *A* section of V-103 (6SN7) which is connected as a d-c amplifier driving the *B* section. The *B* section acts as a phase inverter which drives the following push-pull stage.

The push-pull stage consists of V-104 and V-105. A dual potentiometer (R-125) is provided to regulate the gain and thus regulate the amplitude of the sweep. This control is marked V-AMP and is located under the door of the CRO chassis. The output of the vertical amplifier is fed directly to the vertical deflection plates of the CRO, a type 3FP7 tube having a long-persistence screen.

Trigger Circuit

The trigger circuit is a flip-flop arrangement having one stable and one unstable limiting condition. The twin triode, 6SN7 (V-107), is normally nonconducting in the *A* section and conducting in the *B* section from which the output keying pulse is derived. The differentiated timing pulse from the *A* section of the multivibrator (V-101) through C-109 drives the grid of the *A* section of the trigger tube positive, causing it to flip into the conducting state. The resulting pulse from the plate of the tube cuts off the *B* section, discharging condenser C-110, C-111, or C-112, depending upon which one is in the circuit. The time required for the condenser in the grid circuit of the *B* section to discharge determines the length of the transmitted pulse. When the charge leaks off the condenser, the *B* section again conducts which flops the *A* section back to normal, nonconducting state. The selection of condenser C-110, C-111, or C-112, is made by the range switch and, by this means, a longer keying pulse is used with the longer range scales. The positive keying pulse taken from plate resistor R-136, is then fed to the keying tube of the 80-kc oscillator, located in the lower chassis. All circuits described previously have been located in the (upper) CRO chassis, which is shown in Figure 10. The wiring diagram for this chassis is shown in Figure 15. The interconnection between the upper and lower chassis are shown in Figure 16.

80-kc Oscillator

The oscillator, located in the lower chassis (Figure 17), is controlled by a keying tube V-201 which is a twin triode 6SN7, with the two sections of the tube operating in parallel. The positive pulse from the trigger circuit, through the coupling condenser C-201, permits

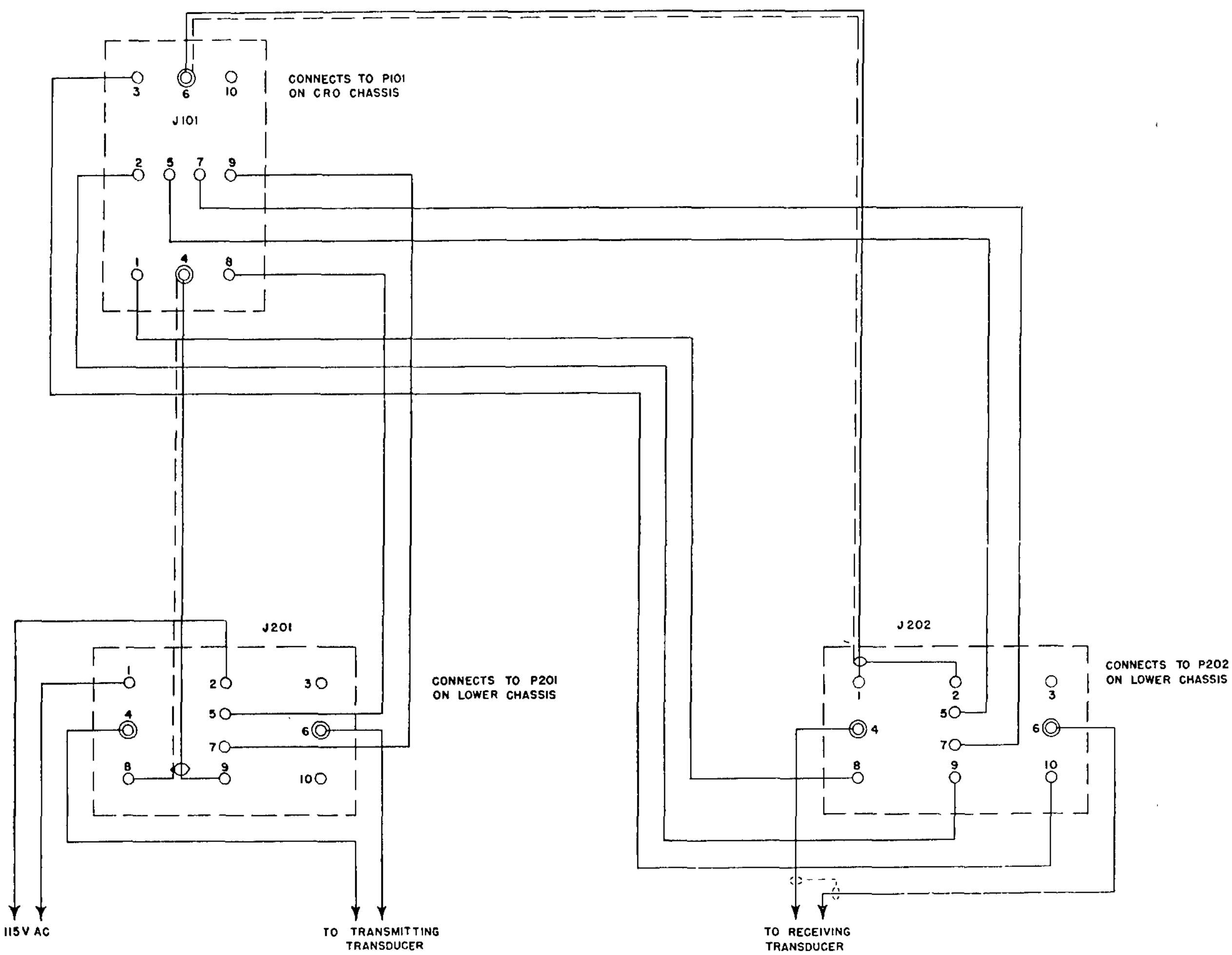


FIGURE 16. Interconnection wiring diagram for SESE Model III.

the keying tube to conduct, and controls oscillation.

The balanced oscillator (V-202) is a twin triode, 6SN7. The frequency of the oscillator is fixed at, or near, 80 kc by the constants of L-201 (which is a mid-tapped iron-core toroid) and its associated condensers, C-204 and C-205. These elements are not provided with adjustments and it is necessary, therefore, to line up the receiver with the oscillator rather than to attempt to adjust the oscillator frequency.

Power Amplifier

The power amplifier is of the push-pull variety consisting of two tubes, V-203 and V-204, which are 6L6 beam power amplifiers. The amplifier is coupled to the transmission line by means of an impedance matching transformer (T-201). The gain of the amplifier is regulated by means of a dual potentiometer (R-204) in the grid circuits of the tubes. This control, which is one of the two principal controls, is identified as output. The maximum output of the amplifier is approximately 10 watts.

A set of toroidal matching coils, L-202A and L-202B, are provided for balancing out the capacitance of the transducer. These coils should be located as near to the transducers as possible. A standard Navy 20-wire junction box located in the forward torpedo room is used for this purpose.

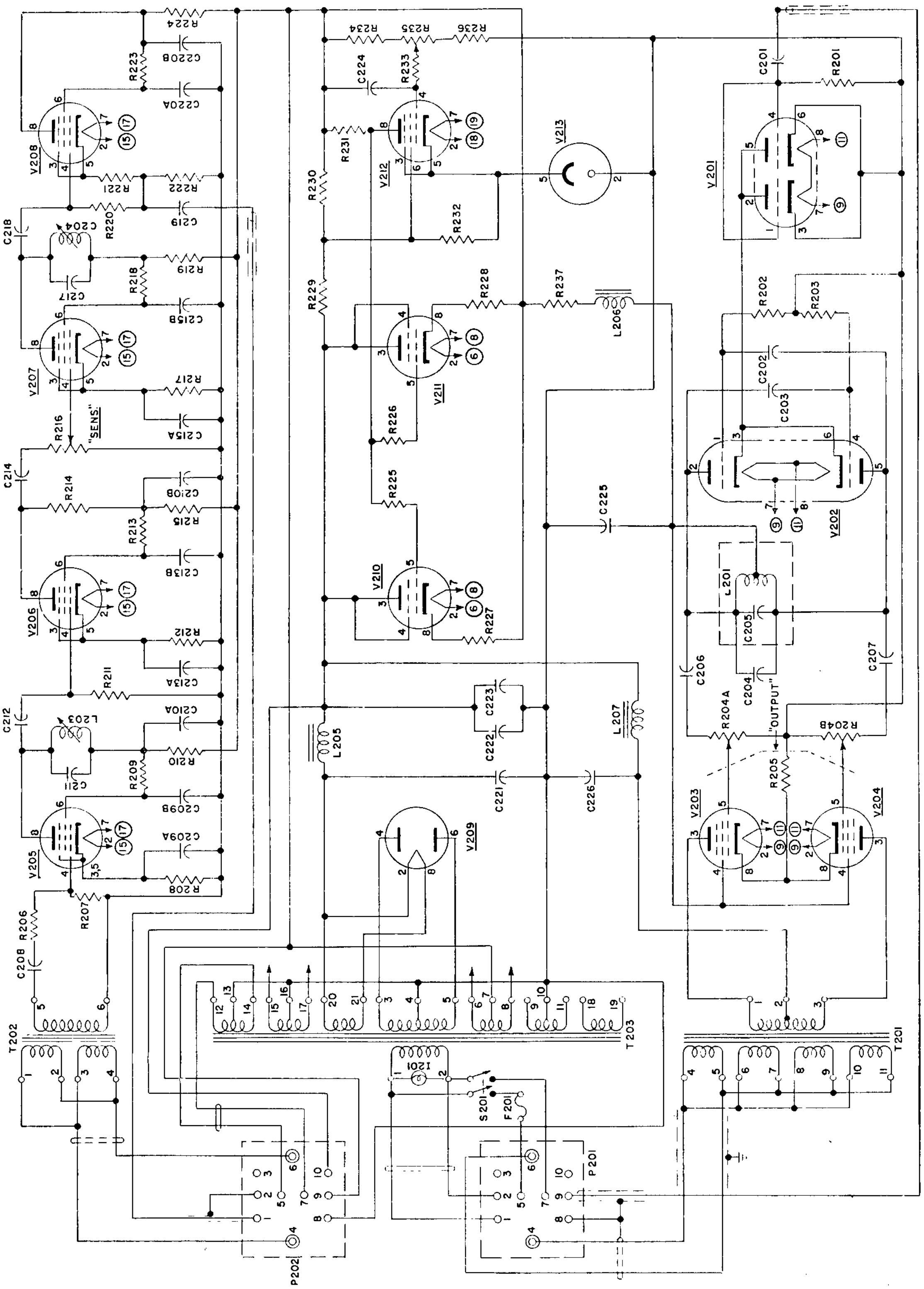


FIGURE 17. Lower chassis wiring diagram for SESE Model III.

Transmitting and Receiving Transducers

The transmitting and receiving transducers are mounted together in a unit as shown in Figure 9. The assembly consisting of the two transducers in the fabricated framework is identified as UCDWR Type FH. The transducers are identical and are designated by the UCDWR Type No. GD16. The construction of one of these identical units is shown in Figure 7.

Receiver Amplifier

The receiver amplifier is a four-stage, high-gain, tuned amplifier. The first and third stages are resonated at 80 kc by means of slug-tuned plate inductors L-203 and L-204. The first stage uses a 6SH7 triple-grid amplifier (V-205). The second stage is resistance coupled. The second and third stages use 6SJ7 triple grid amplifiers (V-206 and V-207). The fourth stage is a 6SJ7 (V-208) used as a cathode follower. A gain control (R-216) is located in the input circuit to the third stage of the amplifier. This is one of the principal SESE controls and is identified as sensitivity (marked SENS). It is located on the lower right of the lower chassis.

Horizontal Amplifier

The horizontal amplifier includes V-108, a twin triode 6SN7, and two 6V6 beam power amplifiers, V-109 and V-110. It is similar to the vertical amplifier except for the values of the coupling condensers and for the control of the amplifier gain. In the horizontal amplifier, a potentiometer (R-137) in the input to the grid circuit of the *A* section of V-108 is used to control the gain. This control is identified as H-AMP and is located on the CRO chassis under the door. A potentiometer (R-147), located in the common cathode circuits is used to position the CRO trace. This control is marked H-POS and is also located under the door on the CRO panel.

Power Supplies

Two separate power supplies are provided. The unregulated CRO power supply is located in the CRO (upper) chassis. The regulated power supply is located in the lower chassis.

CRO Power Supply. The CRO power supply provides the high-voltage (2,300 v) supply for the operation of the CRO tube and also 6.3- and 2.5-v filament supplies. The power supply includes the transformer (T-101) and 2X2 full-wave rectifier (V-111), a 1-μf condenser, C-116, as well as the usual voltage divider network.

The voltage divider network of the CRO power supply is provided with two adjustable elements. Potentiometer R-151 adjusts the voltage which is applied to the grid of the cathode-ray tube, and thus controls the intensity of the electron beam. This control is identified as intensity (INT.) and is located under the door of the CRO chassis. Potentiometer R-154 regulates the voltage which is applied to the focus anode of the CRO, and thus regulates the sharpness of the CRO trace. This control is identified as focus and is also located under the door of the CRO chassis.

Regulated Power Supply. The regulated power supply provides (1) a source of regulated voltage for the operation of the multivibrator circuits, and (2) plate and filament voltages. It includes the transformer (T-203), a 5U4G full-wave rectifier (V-209) and the associated filter components. The transformer provides 900 v, 6.3 v (five separate windings), and 5 v. An electronic voltage regulator provides a regulated 300-v supply for the multivibrator. The two 6Y6 beam power tubes (V-210 and V-211) are connected in parallel and act as the regulator tubes. A 6SJ7, triple-grid amplifier (V-212), in series with a gas voltage regulator VR-105 (V-213), acts as the control tube. The plate voltage for the vertical and horizontal amplifiers and for the power amplifier is taken from the 450-v unregulated section of the regulated power supply. The balance of the equipment operates from the 300-v regulated section of the power supply. The output voltage is adjusted by means of potentiometer R-235.

9.5.6 Performance

Three Model III equipments were installed on submarines. Good soundings were possible throughout the range of the instrument at sur-

face speeds up to 16 knots; depths up to 50 fathoms could be measured at top speed. Deep water soundings up to 300 fathoms were made by means of the multiple depth sounding techniques. As a test of shallow water accuracy, the boat was flooded-down at the laboratory dock until the hull touched the bottom. Under these conditions, the bow-mounted transducers were just 6 ft above the bottom. At this point, the SESE dial indicated a depth of zero fathom, exactly as it should. To check the security of the system, overhearing tests were conducted on a training boat equipped with standard listening gear. The SESE signal could not be detected at any time during these tests.

9.6 CONCLUSIONS

Accomplishment of Objective

The SESE Model III is believed to have achieved the four primary objectives: accuracy, security, simplicity, and small size. The SESE does not and was not intended to supplant the high-powered fathometer equipment of the submarine. However, for ranges up to the maximum calibrated depth (105 fathoms), the SESE makes use of the standard fathometer unnecessary, and has the advantage of not revealing the submarine's presence to an enemy observer. The experience of SESE-equipped vessels has definitely established the dependability and tactical value of this equipment. It has been credited with the safe return of submarines which were forced to operate in dangerously shallow waters where the use of any other available sounding equipments would have been a hazardous undertaking.

Limitations

Only two limitations of consequence are known to exist: the low power and the range calibration which does not exceed 105 fathoms. The power available has generally permitted soundings over the calibrated range. Greater depths can and have been measured under favorable conditions by the use of a simple calculation involving any two successive readings of the dial. This technique involves the multiple echo effect (see Section 9.5.4). This multiple echo effect presents an advantage in that it permits extension of useful range of the equipment, but it does so at the cost of a certain amount of uncertainty regarding the accuracy of readings. In depths less than 105 fathoms, the true depth is assured by investigating the deeper ranges first; the deepest sounding possible gives the correct depth. It should be pointed out that this technique is contrary to the doctrine established for Navy Type NM echo-sounding gear, in which the shallowest depths are investigated first.

9.6.1 Possibilities for Future Investigation

There are a number of possibilities which might be suggested as being profitable for future investigation.

Redesign of the Transducer. A transducer having smaller size, and at the same time capable of handling greater power at higher efficiency, would permit installation on the hull without the structural modifications necessary when the present equipments are installed in the keel.

Extension of Range. Since under favorable bottom conditions depths of 300 fathoms have been measured, it might be advisable to provide one or more additional range scales in order to extend the usefulness of the equipment. This would result in a definite psychological advantage as it would remove the necessity of using the multiple-echo formula which is a handicap in extended range at the present time.

Redesign of Equipment. A redesign of electric circuits and mechanical arrangement might reduce the number of tubes required, and could profitably separate the equipment into two parts; one an indicator, and the other a power unit. This would permit short power leads to the transducers, and would also permit installation of the control and indicator unit in the conning tower. This is considered very important because of the crowded conditions known to exist aboard submarines.

Improved Transducer Mounting. Although this idea might be combined with item number one, the objective is slightly different. It would be advisable to provide for shifting of the beam of the transducer in order to permit a much

greater forward angle, when desired, so that the equipment would be even more helpful in avoiding running aground. This might be accomplished by means of mechanical movement of the transducer, by electrical shifting of the beam pattern, or by providing a number of transducers, each having a slightly different mounting with respect to the keel line. This later method would be most practical if smaller transducers capable of blister mounting could be provided.

Improved Recording System. Operation of the equipment would be simplified if means could be provided for automatic operation of the equipment by a direct recording system. A number of possibilities have been suggested but were not developed. For some reasons it might be advisable to provide a calibrated CRO with an A-scan type of presentation. This would permit more rapid reading of the instrument since it would only be necessary to shift ranges and then read the position of the echo pip on the calibrated scale. For other reasons, it might be advisable to eliminate the CRO and to use some other method of indication, such as a calibrated meter. This would involve abandonment of many of the essential features of the SESE, but such possibilities should not be overlooked.

Chapter 10

SUBMARINE SONAR 692

692 Submarine Sonar

The 692 submarine sonar is a multi-purpose experimental system designed for use on submarines. Utilizing the WFA three-section crystal projector, it provides, in addition to conventional service, short pulse echo-ranging in the 10- to 50-kc band, and short pulse small object detection of underwater obstacles such as mine fields. Listening over the band of 200 to 60 kc, with BDI indication for frequencies between 15 and 60 kc, is also possible with the 692 submarine sonar. Additional features incorporated are maintenance of true bearing [MTB], automatic target following [ATF], automatic torpedo detection, and self-noise monitoring. The development program had not been concluded at termination of NDRC support, and no tests were made on the echo-ranging portion of the 692 submarine sonar. Preliminary operational tests of the listening system, however, showed good sensitivity and bearing accuracy. Development is being continued by the Bell Telephone Laboratories.

10.1 INTRODUCTION

At the time work was begun on the 692 sonar, the standard systems in use on submarines were rather limited in scope. They consisted for the most part of a JK-QC projector combination for listening and echo ranging over a fairly narrow band of frequencies in the region of 25 kc. This was supplemented by the JP system which was entirely separate and covered the audible range. Later adaptations extended the JP into the supersonic range. The training mechanism used with the JK-QC projector did not permit the rapid scanning needed to identify low intensity signals. The JP was trained manually and could differentiate signals but required considerable physical effort. None of these systems employed visual bearing indicators of the phase sensitive type. The echo ranging available with the QC projector was the standard 25-kc long pulse type used in antisubmarine work.

Looking toward improved submarine sonar systems, the outstanding need was for a system

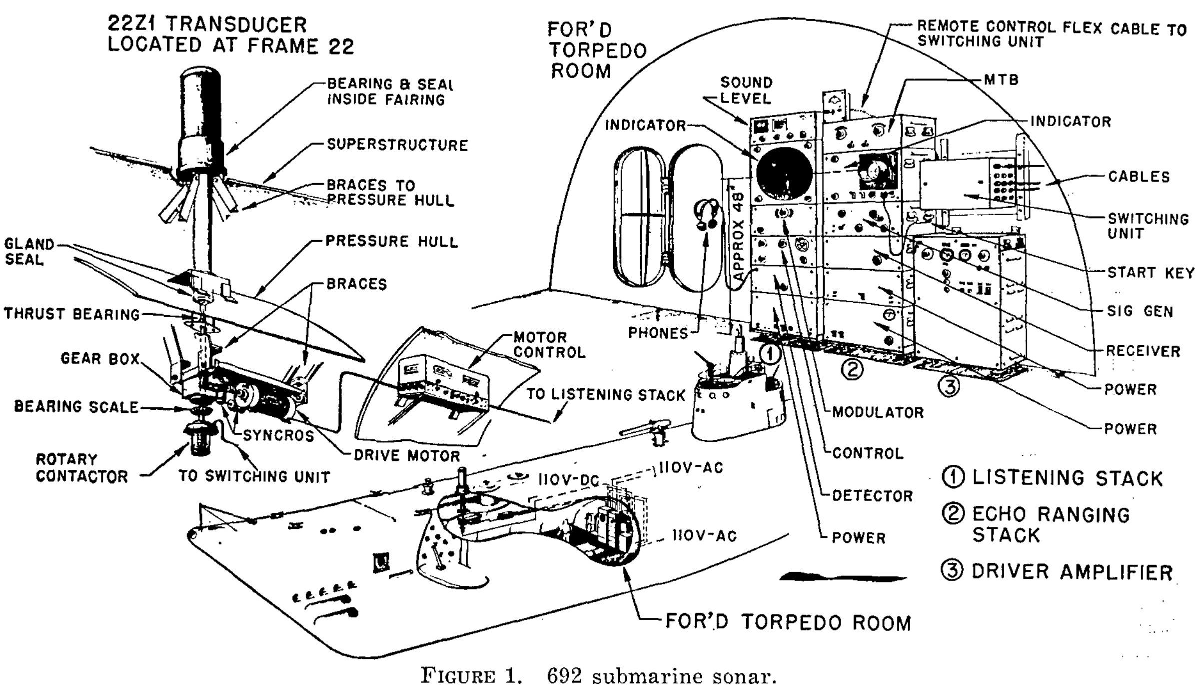


FIGURE 1. 692 submarine sonar.

which would supply information to the submarine commander operating below periscope depth, comparable to what he can obtain with his periscope. The best possible sonar will not equal the capabilities of periscope and radar. Low-frequency sonar may excel in range but will not compare in accuracy. High-frequency sonar will provide good accuracy but will fall short in range. Since the important factor in deep operations is security, echo ranging of any kind is not the final answer. Triangulation ranging on sound bearings is a possibility. Sound bearing accuracy then becomes of primary importance and a requirement of ± 0.1 degree is not unreasonable. This in turn imposes certain requirements on the training system as well as on the projector. A complete sonar system should also include means for scanning mine fields, self-noise monitoring, torpedo detection, location of depth charges, sonic depth finding, and underwater communication.

The equipment designated 692 submarine sonar, from the OSRD contract number, was designed to facilitate the investigation of sonar requirements rather than to supply a working system. Its scope, therefore, is quite broad as regards component features, controls and adjustments, and its parts are not completely integrated as they would be in a standard equipment.[a]

The original project called for the development of a listening system[b] only, which was to be supplemented with a standard surface-vessel type of echo-ranging equipment (QJB) operating at 24 and 50 kc. Subsequently the project was enlarged to include the development of a short pulse, high peak power, echo-ranging equipment to operate over the range of frequencies from 10 to 50 kc. Finally, it was agreed to include in the echo-ranging system a PPI for mine detection.

[a] In order to include the 692 sonar system in this volume, it was necessary to confine this material to a generalized description of the system, omitting actual circuit details and operation. These generally follow component circuits described in this volume and Division 6, Volume 14. Complete information on actual circuits and their performance under experimental conditions may be found in reference No. 1 which has been microfilmed.

[b] Details of listening equipment embodied in the 692 sonar are discussed separately in Division 6, Volume 14.

System Requirements

The initial requirements included continuous search at speeds up to 60 rpm with an indicator, preferably not of the CRO type, rapid shifting between continuous search and hand training, the latter to be accurate within $\pm$ 0.5 degree or better, using a phase-sensitive bearing indicator; automatic or aided target tracking and maintenance of true bearing (see Section 3.7). The self-noise of the training system was to be low enough as not to affect listening. The listening system had to be capable of differentiating between two targets of the same intensity when they are 5 degrees or more apart. The frequency range was to be from 15 to 50 kc with provision for listening to suitable bandwidths with both loudspeaker and headphones.

The completed system, which has been delivered to the U. S. Navy at New London, Connecticut, contains all the features outlined above. It includes a three-section projector which is a prototype of the projector used with the WFA sonar. This is one of several features which the two systems have in common and which were derived from the early development work on Contract No. 692. The indicator for the listening system displays the location of targets by means of an azimuth circle of lights and has proved adequate for tracking torpedoes. The maintenance of true bearing feature operates satisfactorily either with a step-by-step or synchro-type compass repeater. Either *continuous search listening* [CSL], *automatic tracking* [AUTO], or *hand training* [HAND] may be rapidly selected on one switch.

System Performance

Measurements of the bearing accuracy of the automatic target tracking system at sea indicated 0.15 degree standard deviation of sound bearings with respect to the stern of a target ship. This means that the bearing accuracy of the 692 sonar will be well within the $\pm$ 0.5-degree requirement. The self-noise of the training system is well below the lowest ambient noise levels at distances greater than ten yards

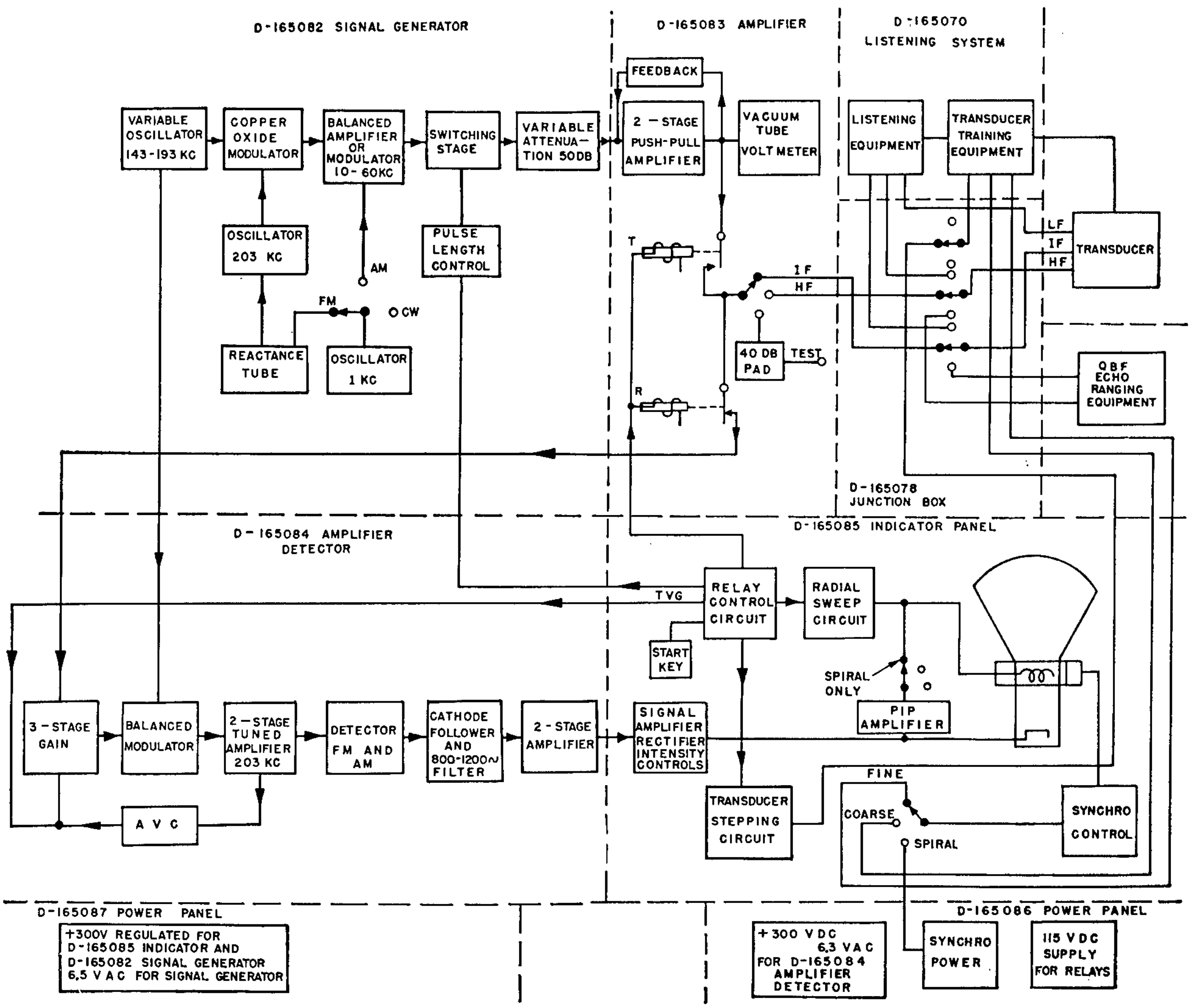


FIGURE 2. Block diagram of echo-ranging system.

from the projector. The self-noise picked up by the projector is below the internal noise in the system except at frequencies below 1,000 c and at speeds in excess of 20 degrees per second. The internal noise is below the lowest ambient noise levels in the intermediate range of frequencies and only slightly above at the ends of the frequency range. The useful frequencies extend from about 200 c to 60 kc, but the band below 10 kc is used only for detection listening and not for bearing determination on account of its poor directivity.

The ability of the system to differentiate between targets depends upon the beamwidth of the projector. By avoiding the use of side lobe reduction which broadens the beam, the discrimination at frequencies above 50 kc is sufficient to separate two targets of equal signal strength 5 degrees apart. This was confirmed experimentally.

Although the field trials of the 692 sonar were of a limited nature, sufficient data were obtained to confirm the above statements on performance. No trials were made of the short pulse echo ranging equipment except to check its operation. It is expected that further trials will be made by the Navy to obtain additional information on the capabilities of the system as a whole.

10.2 DESCRIPTION OF EQUIPMENT

The four major components of the 692 sonar are the projector, projector training system, the listening stack,[c] and the short pulse echo-ranging stack. The echo-ranging system is itself composed of a number of units each of which is described separately. A block diagram of the short pulse echo-ranging system is given in Figure 2.

10.2.1 Projector

The design requirements called for a projector to cover the range from 200 c to 60 kc for listening and from 10 to 60 kc for echo ranging. Also, the unit should not be more than 36 in. high and should be in a cylindrical case not more than 13 in. in diameter. Since 13-in. tubing was not commercially available, the latter requirement was revised to 14 in. A requirement that the unit be capable of withstanding gun blast and a static pressure of at least 400 psi was also specified.

By specifying both size and frequency range, the more important characteristics of the projector, including its directivity, were defined. It was agreed that the requirement could best be met, at the time, by employing a three-section projector; one section to cover the low-frequency range from 200 c to 15 kc; a section consisting of a modified QBF projector to cover the intermediate frequencies from 15 to 30 kc; and a high-frequency crystal plate of the same width but half the height of the QBF plate to cover the range from 30 to 60 kc. The low-frequency unit consists of a line of four dia-

FIGURE 3. 692 submarine sonar projector mounted on the deck of a submarine.

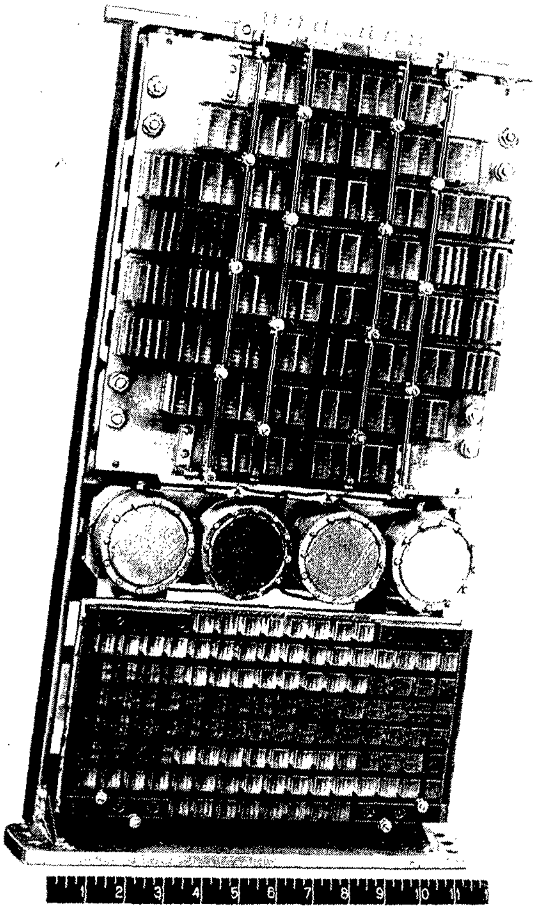


FIGURE 4. Front view of crystal arrays in 692 projector.

[c] The listening stack is described in Division 6, Volume 14.

phragm-type hydrophones, each containing a single block of crystals of the type used in the QBF plate. These four units are mounted between the high and intermediate frequency sections. The high-frequency unit is mounted at the top in order to minimize diffraction about obstacles on the deck of the submarine. The installed projector is shown in Figure 3.

The high-frequency unit was made the same width as the other units in order to obtain maximum horizontal directivity. However, its height was made only one-half the width so that the vertical directivity pattern would not be too sharp. Too narrow a beam in the vertical plane would unduly restrict the area from which signals could be received. Although none of the units in the 22Z-1 projector was tapered in the horizontal plane, both the h-f and i-f units were tapered in the vertical plane to reduce the effect of reverberation.

In addition to meeting the Navy requirements, the design was aimed at keeping the absolute efficiency as high as possible over the listening range, thereby keeping the thermal noise low with respect to ambient water noise. This is particularly important at the higher frequencies. An effort was also made to keep the phase shift between the halves of the projector to a minimum in order to provide good balance for the phase sensitive detector.

Crystal Arrays

The arrays are mounted on a steel frame which bolts to the housing. Front and back views of this assembly are shown in Figures 4 and 5. The high-frequency array (h-f) is at the bottom of the photograph, the sonic or low-frequency array (l-f) is in the center and the intermediate-frequency (i-f) array from 10 to 30 kc is at the top. When mounted topside on a submarine, this order is reversed and the i-f array is at the bottom.

As shown in Figure 5, the h-f and i-f arrays are supported at the four corners by brackets which are mounted in a shock-insulating type of rubber support developed for the QBF projector. The l-f array is similarly shock mounted to a cross member of the frame. The frame also supports terminal strips, a wiring form, repeating coils for the h-f and l-f arrays and protective neon lamps. These are not shown in the photographs.

Projector Characeristics

The characteristics of the projector, to a large extent, determine the capabilities of any sonar system. No refinement of the electrical circuit can make up for deficiencies in the projector, particularly in regard to its internal noise threshold and its directivity. Frequency response is not basically important but may be used to calibrate the output in various listening bands in terms of sound pressure in the water.

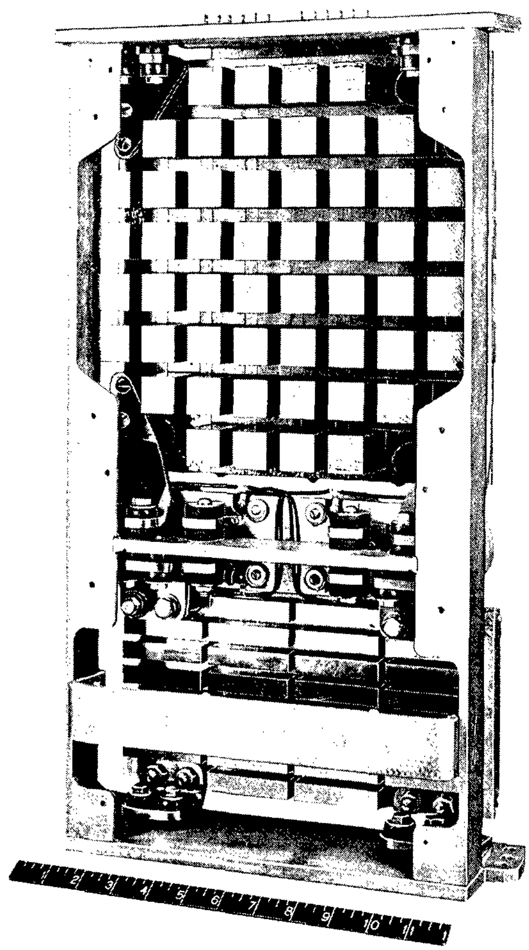


FIGURE 5. Rear view of crystal arrays in 692 projector.

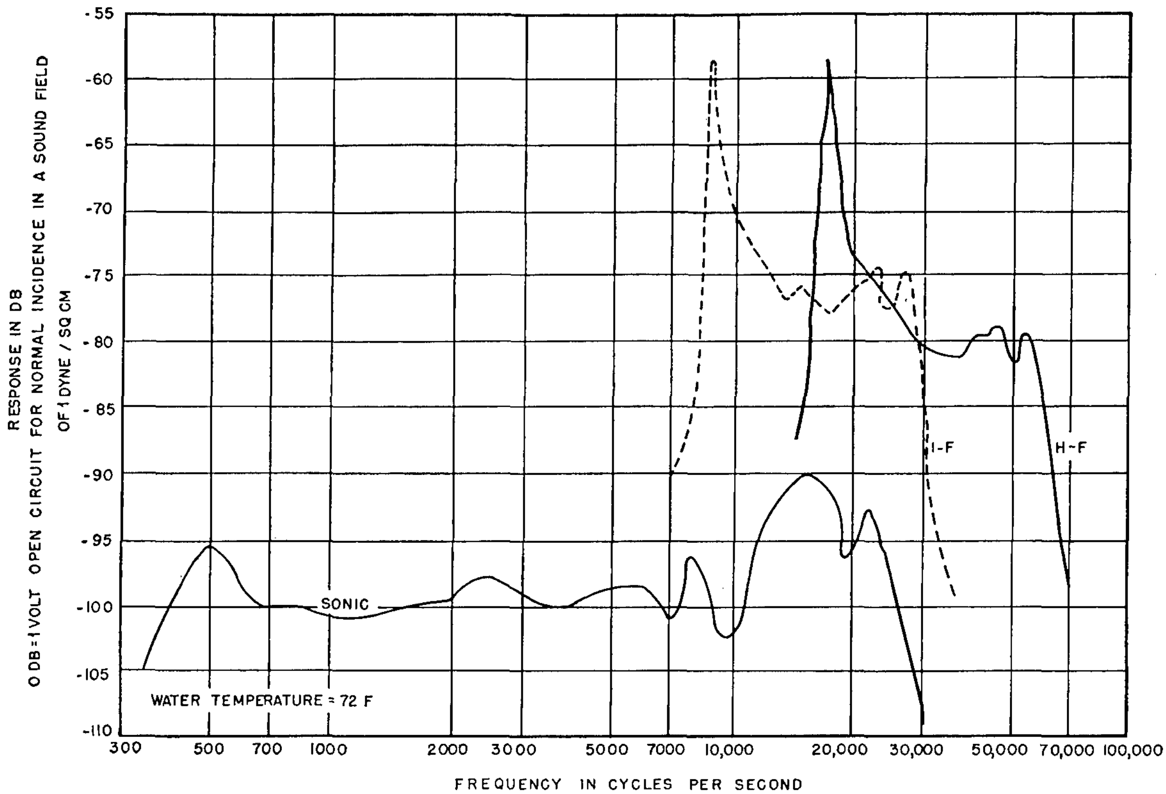


FIGURE 6. Open circuit calibration of WFA No. 22-Z projector used as a hydrophone.

Frequency Response. The open circuit calibration of the projector used as a hydrophone is shown in Figure 6. This type of measurement is significant from a design standpoint. It shows a high peak at the cutoff frequency of the transformer which is compensated for in the amplifier input transformer.

The calibration of the h-f and i-f sections of the projector when used to transmit sound into the water are shown in Figure 7. The h-f unit is somewhat more efficient in this respect primarily because of a better directivity index.

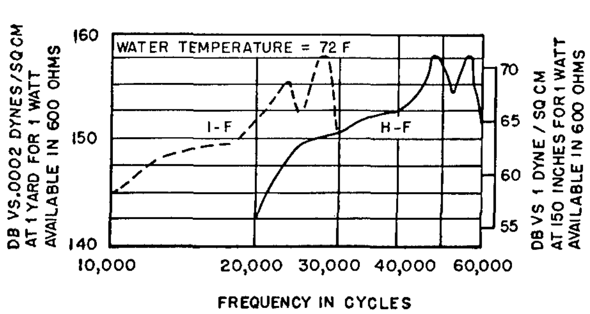


FIGURE 7. Calibration of h-f and i-f sections of WFA No. 22-Z projector.

Internal Noise. The internal noise spectra for the projector are shown in Figure 8. The low-frequency unit is poorest in this respect. A higher level of internal noise can be tolerated at the low frequency because the spectrum of ambient and self-noise rises toward the low end. Furthermore the directivity becomes less and thus a higher level of ambient noise is accepted. However, the low-frequency unit is limited by internal noise wherever low ambient and self-noise levels prevail.

Directivity. The calculated directivity patterns for the i-f array at 24.5 kc in both the horizontal and vertical planes are shown in Figure 9A. These patterns show the effect of the taper, which reduces the side lobes at the expense of the main lobe, which becomes larger. The patterns also show that the directivity of the individual blocks has a slight effect on the side lobes.

An array with taper in the horizontal plane is considered desirable from an echo ranging standpoint as the reduced side lobes will minimize the possibility of errors due to false echoes.

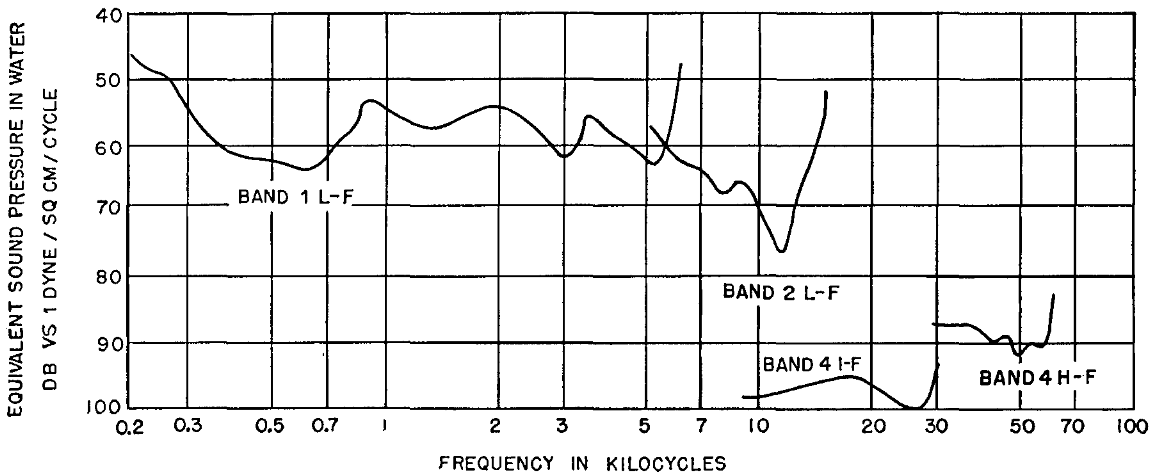


FIGURE 8. Internal noise spectra of WFA No. 22-Z projector of 692 submarine sonar.

However, when listening with a phase-actuated locator (BDI) (see Section 5.2.2) such an array is not so desirable from an interference standpoint as a linear array. This is shown by the curves in Figure 10 where the bearing error in degrees is plotted against angular separation between the target and an interfering signal of equal intensity for both tapered and linear arrays. It can be seen that the bearing error when using a tapered array is greater than that for a linear array when the angular separation between target and interference is between 9.5 and 17.5 degrees.

The measured directivity patterns of the i-f array in the horizontal plane at 12, 18, 24, 30, and 36 kc are given in Figures 9B, 9C, 9D, 9E, and 9F, respectively. With the exception of the pattern for 36 kc these curves show increase in directivity with frequency which is in agreement with the computed variation of directivity index shown with frequency in Figure 11. The measured pattern at 24 kc, Figure 9D, compares favorably with the calculated pattern in Figure 9A for 24.5 kc. The pattern at 36 kc is typical of what happens to the directivity outside of the useful range where the response falls off and the phase conditions over the face of the projector begin to vary.

The calculated horizontal and vertical directivity patterns at 49 kc for the h-f array are shown in Figure 12A. The measured horizontal directivity patterns for this array at 30, 40, 50, 60, and 80 kc are shown in Figures 12B–F.

The l-f array in the 22Z-1 projector has relatively low directivity because of dimensional restrictions. It is essentially nondirective in a vertical plane and its measured directivity in a horizontal plane for 2.2, 6, 9, and 15 kc is shown in Figure 13. It will be observed that at 2.2 kc there is practically no directivity and at 15 kc there is only moderate directivity. On account of its poor directivity this array is used for listening only and no attempt is made to use the phase-actuated locator with it because of the inability to distinguish among sound sources.

10.2.2 Projector Training System

The methods employed in training the projector have a direct bearing on the performance of the entire sonar system. To provide the bearing accuracy and speed range sought for in this training system it was necessary to employ methods other than those used in existing sonar systems to meet the more stringent requirements discussed below.

Performance Requirements

Several requirements were initially emphasized. First it was considered desirable to be able to align positively the acoustic axis of the projector within plus and minus 0.1 degree of any bearing desired. For following targets, a

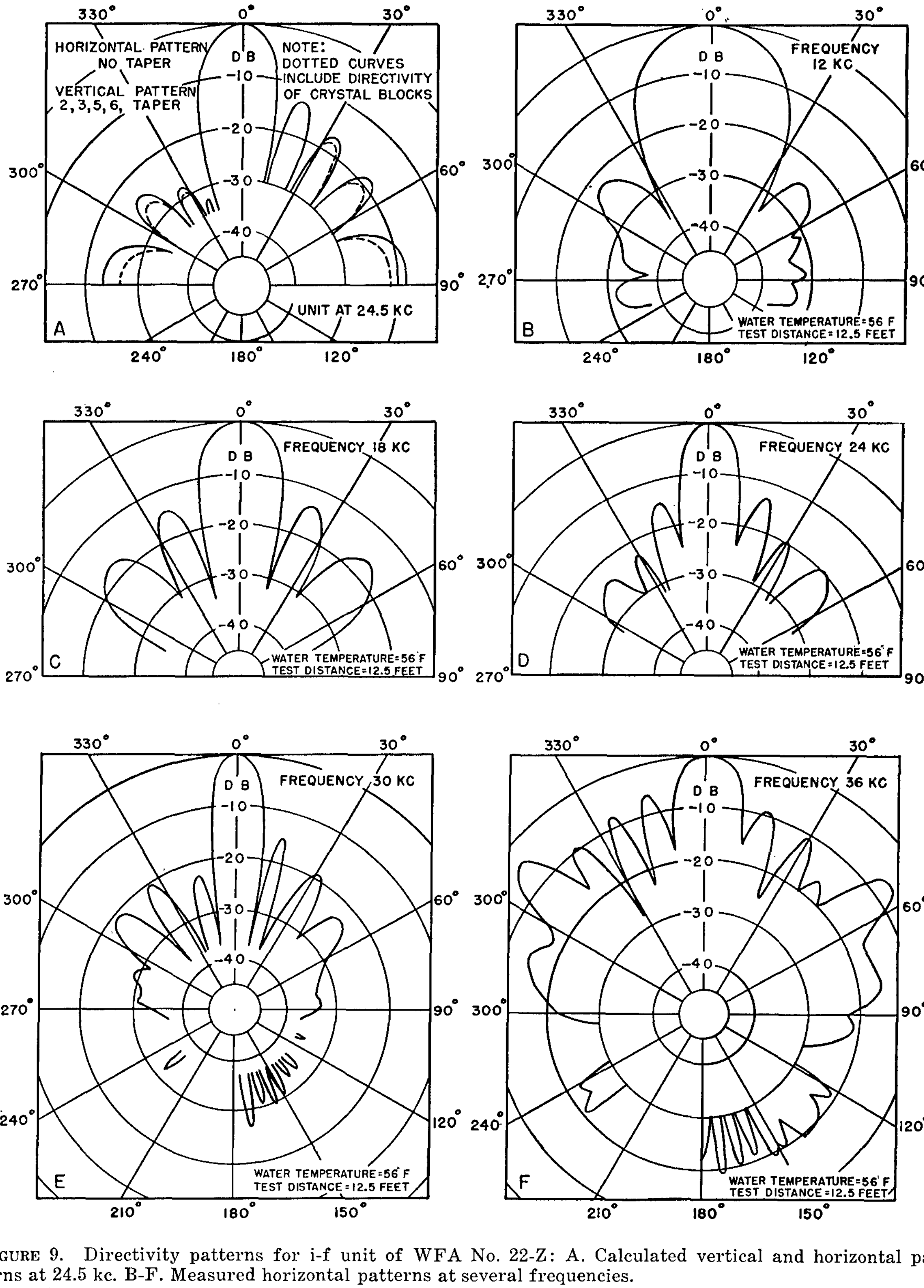


FIGURE 9. Directivity patterns for i-f unit of WFA No. 22-Z: A. Calculated vertical and horizontal patterns at 24.5 kc. B-F. Measured horizontal patterns at several frequencies.

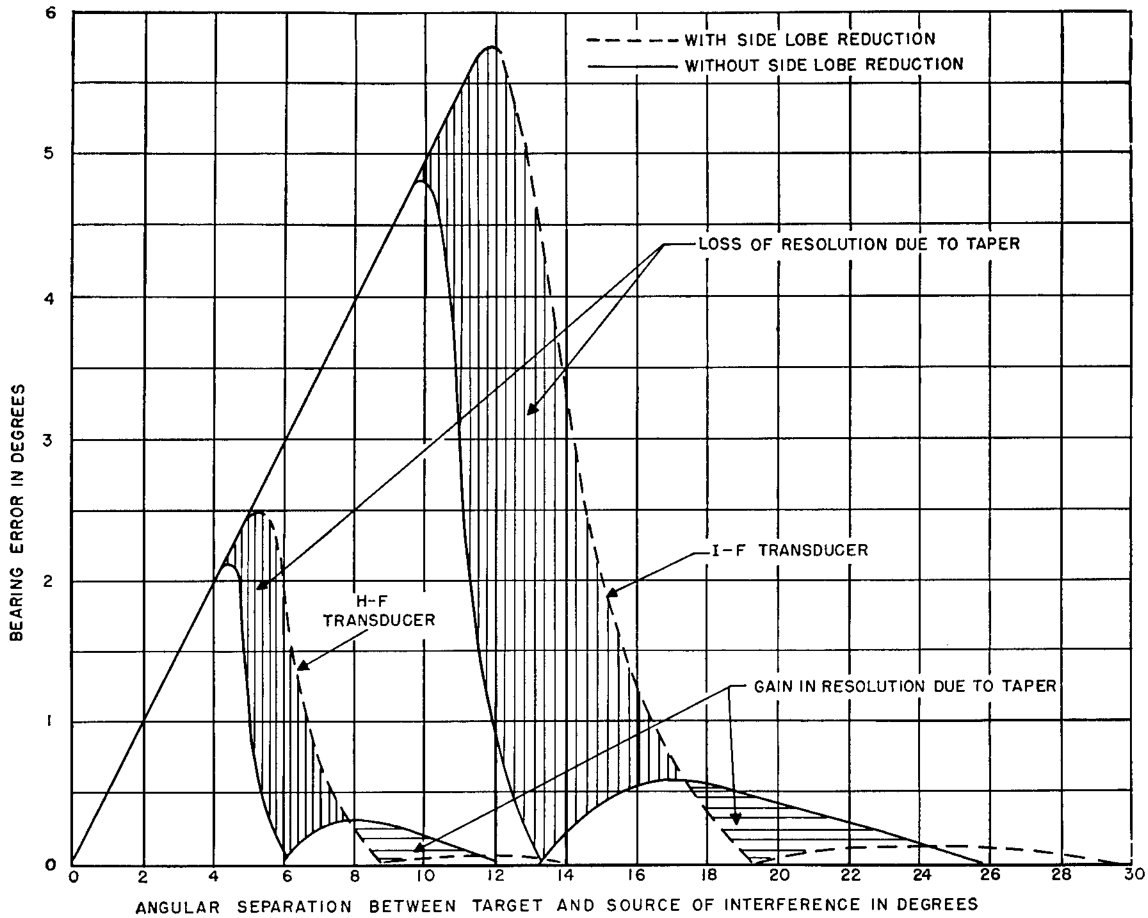


FIGURE 10. Error of phase-actuated target bearing indication caused by an interfering signal of equal intensity.

smooth continuous shaft speed range adjustment was sought from about 0.1 degree per second for slow ships at long ranges, to about 4 degrees per second for fast ships at close ranges. Higher shaft speeds up to about 30 degrees per second were considered necessary for quickly slewing from one bearing position to another and a single high speed of about 360 degrees per second was needed for continuous search. This wide range of shaft speed had to be accomplished without discontinuity, except between the slewing and search speeds, by a mechanism that could be controlled from a remote position and which would neither introduce noise into the listening system nor radiate sufficient sound into the water to endanger the security of the ship. The noise problem was considered of prime importance and much attention was given to design features that would be expected to reduce the mechanical vibration transmitted to the training shaft or to the ship's hull. Another characteristic of the training system that was necessary to consider at the outset was its adaptability to some form of automatic target tracking arrangement.

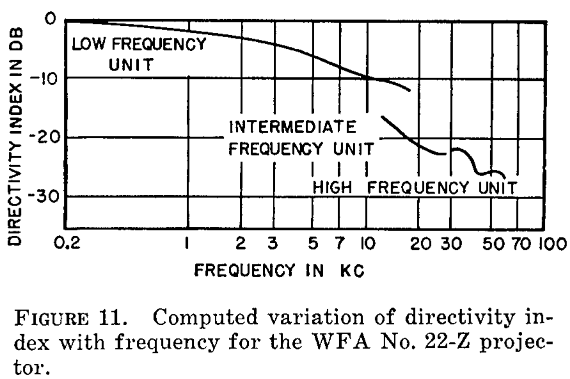


FIGURE 11. Computed variation of directivity index with frequency for the WFA No. 22-Z projector.

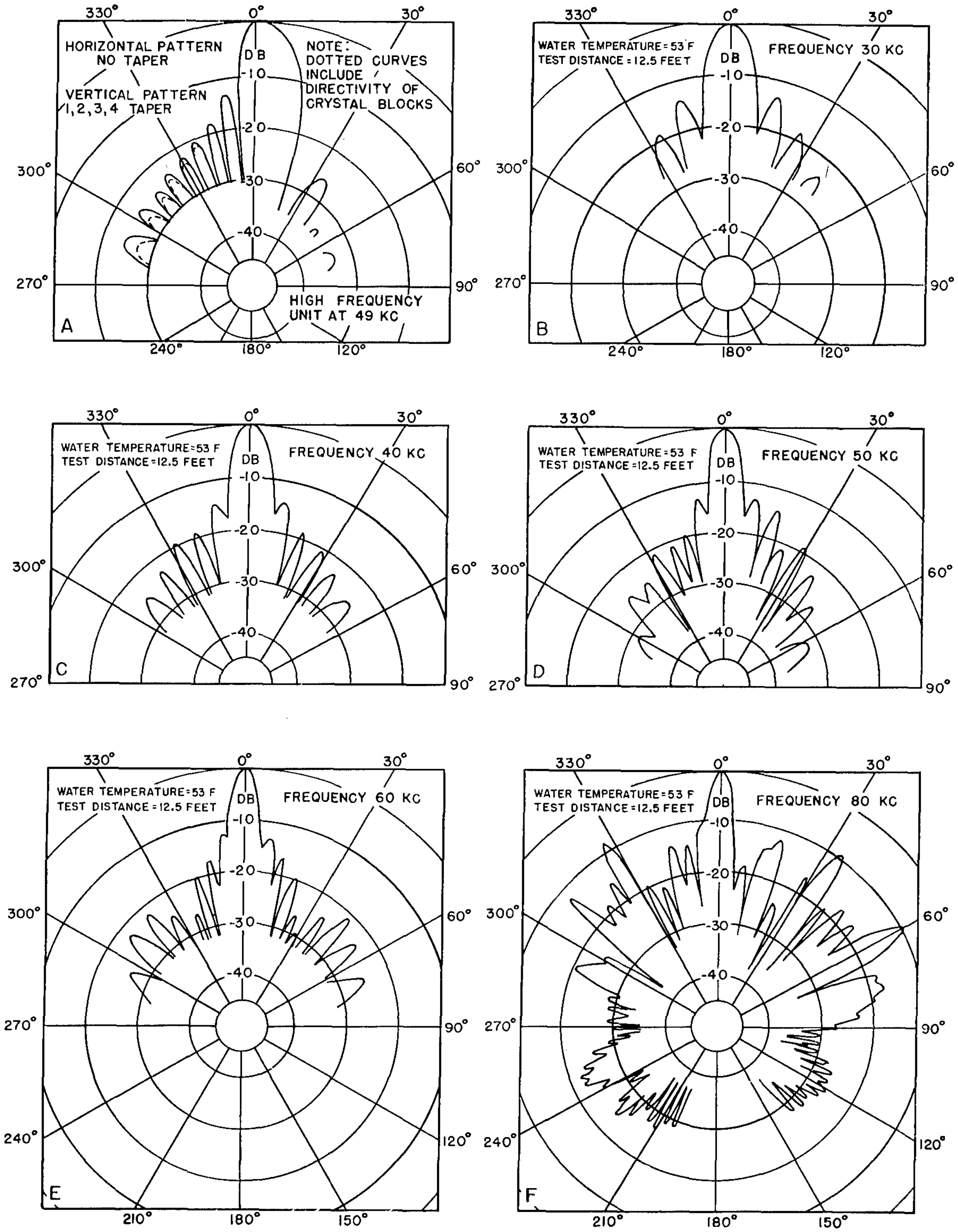


FIGURE 12. Directivity patterns for h-f unit of WFA No. 22-Z: A. Calculated vertical and horizontal patterns at 49 kc. B-F. Measured horizontal patterns at several frequencies.

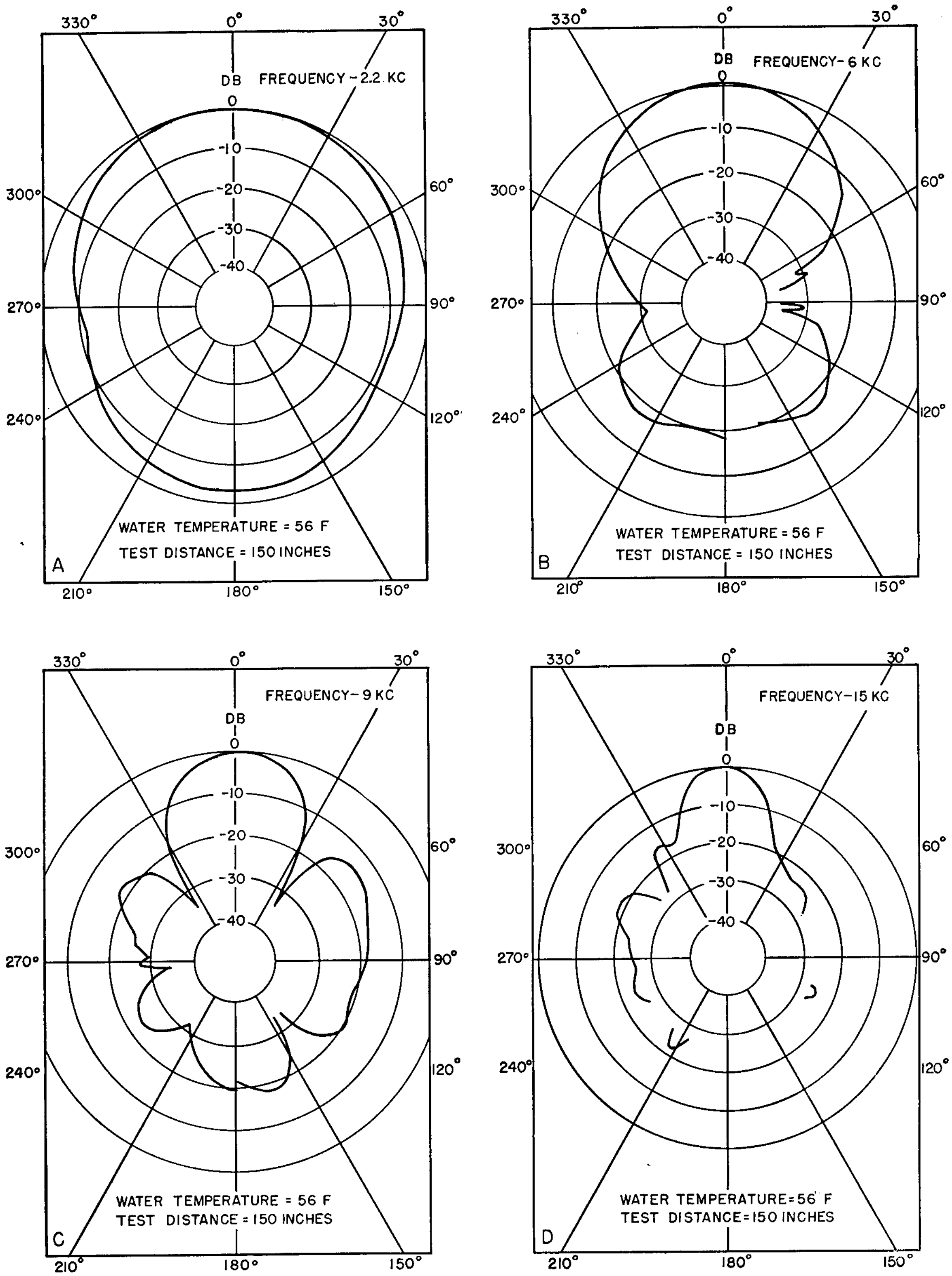


FIGURE 13. Measured directivity patterns for l-f unit of WFA No. 22-Z in the horizontal plane at several frequencies.

Speed Control System

After considering many possible arrangements to cover the wide speed range, such as systems with two or three motors, magnetic and indexing clutches for selecting different gear ratios, mechanisms outside the hull sealed in oil, and differential and planetary gear systems, a drive system was evolved of attractive mechanical simplicity operating through the hull with one motor. This design was made possible by a wide range motor speed control system using mercury contact relays.

Training Mechanism

In order to couple the motor to the training shaft it was necessary to design and build a mechanism assembly with a suitable speed reducing gear and to provide a take-off drive for the coarse and fine synchro generators used for remote bearing indication. The problems involved were unusual because of the high accuracy of training sought, the wide range of speed required, the probability of bearing and gear noise particularly at the search speed, and the necessity of avoiding resonances and excessive displacements in the supporting members. Flexible supports are necessary to isolate the training shaft from undesirable vibrations but excessive displacements in these suspensions would affect the positional accuracy of the training mechanism. Furthermore the suspensions and shaft couplings are important elements in the feedback loop of any automatic target tracking system working through the mechanism; therefore they were designed with mechanical impedance characteristics to keep to a minimum any phase or amplitude effects at frequencies below 10 or 15 c.

The gear system for coupling the drive motor to the training shaft required features that were not obtainable in commercial gear boxes. The training accuracy desired for the system required that backlash and run-out errors in the gears be less than 0.1 degree, which is better than could be assured by any commercial supplier. Also, it was particularly important that gear noise be very low.

The gear system designed and built consists of two worm gears mounted on a hub through which the training shaft can be passed. The worm shaft is carried by ball bearings in an eccentric bushing to permit a close and precise adjustment of the mesh between the worm and gear. Both worm gears and their mating gears were specially cut to order with the highest precision equipment available, and the whole gear system enclosed in an oil-filled housing.

To attenuate any residual gear and bearing noise that might be transmitted to the training shaft, a special flexible coupling was designed for use between the gear hub and the training shaft. This type of coupling introduces a high compliance to all translational forces between the gear box and the training shaft and thereby attenuates noise vibrations having translational motions. However for torsional motions this coupling is very rigid. Measurements were made which showed the torsional displacement to be considerably less than 0.1 degree when transmitting a full load torque of about 30 ft-lb.

The drive motor is, in reality, two separate motors in one housing, as may be seen in the schematic, Figure 14. These have two separate dipole fields with their pole axes at 90 degrees to reduce intercoupling and two separate armatures and commutators, one for low-speed operation and the other for high-speed operation or back-emf generation. Both armatures have winding slots spiralled by one slot in pitch to reduce cogging. The brushes and holding frame were designed to give quiet operation and good commutation for either direction of armature rotation.

10.2.3 Short Pulse Echo-Ranging and Mine Detection System

The short pulse echo-ranging equipment of the 692 sonar is designed to furnish range information with a maximum of security. Because of its lack of tonal quality, the short pulse has a very poor listening differential and when used sparingly it should be practically detection proof. In addition to its use for target ranging, the 692 sonar is equipped to furnish navigational assistance by plotting underwater obstructions such as mines on a repeated pulse

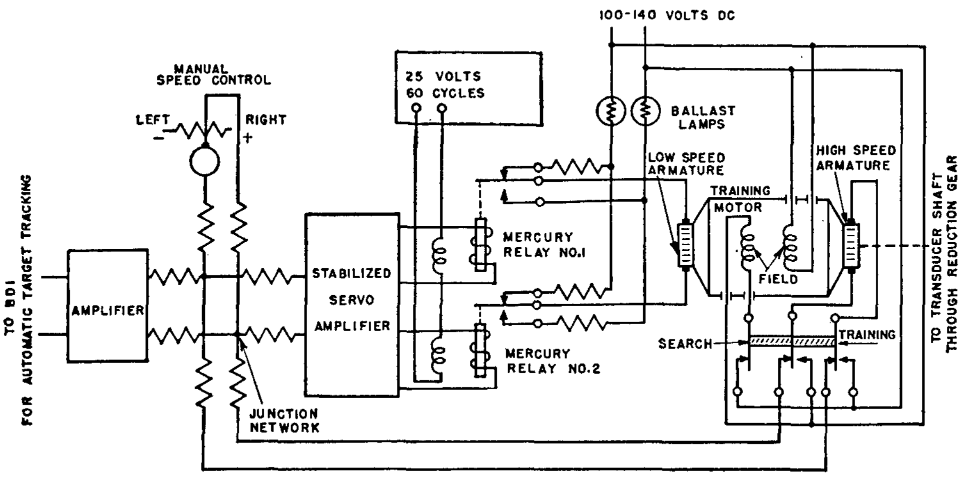


FIGURE 14. Schematic of training control circuit, 692 submarine sonar.

basis. The 692 sonar permits a wide selection of frequency bands which greatly reduces the range over which the pulses can be detected by the enemy unless his sonar system is capable of receiving such frequencies and is tuned to the particular frequency in use at the time. This is particularly useful in exploring mine fields where low powered pulsing is used.

The echo-ranging unit of the 692 sonar equipment, shown in the block diagram of Figure 2, consists of a power amplifier, signal generator, detector, and indicator unit with the necessary power supplies. For single pulse echo ranging, low power is used; for continuous pulsing for detection of underwater obstacles, a low signal level is used so as to decrease the range of possible detection.

The signal for a pulse is obtained from a signal generator. A fixed oscillator (203 kc) is modulated with the signal from a variable oscillator (149-193 kc) to give a continuously variable output from 10 to 60 kc. This signal is coupled to a push-pull stage. For an amplitude-modulated [AM] signal, this stage is used as the modulator and is supplied with 1,000-c modulating frequency from a separate oscillator. For frequency modulation, [FM], the 1,000-c oscillator varies the frequency of the 203-kc through a reactance tube.

The output of the modulator stage is fed to the switching stage. This stage is normally cut off and becomes conducting under control of the pulse length circuit, relay control circuit, and start key.

When the switching stage is conducting it drives the two-stage push-pull power amplifier. During the nontransmit period, the last stages are cut off by high negative bias on the grids. This is reduced to normal class B bias when the pulse length control operates. The low-impedance output is connected to the projector by the *T* relay which operates before the pulse is sent out under control of the relay control circuit. The receiving circuit is opened at this time by the *R* relay. For test purposes a 40-db pad serves as a load.

The receiving circuit consists of three stages of *reverberation-controlled gain* [RCG] (see Section 2.5). This amplified signal is fed to a balanced modulator where the input signal is modulated with the variable oscillator frequency from the signal generator. The output (203 kc) is further amplified in a two-stage tuned amplifier. The output is detected either by FM or AM to give a 1,000-c signal. This signal is amplified in a cathode follower and then is filtered in a 800- to 1,200-c band-pass filter. The 1,000-c signal is then further amplified in two stages.

The signals received are used to control the spot on an oscilloscope tube either as a PPI plot or on a spiral sweep. The spiral is used for

single pulses to give a clear range indication by brightening the spot and by displacing it momentarily toward the center. The indicator panel contains a rotating radial sweep circuit controlled by a synchro motor. On spiral sweep this motor is driven from a synchro generator on the power panel; for PPI the synchro motor is connected to the training mechanism synchros and a stepping circuit is used to train the projector in discrete steps at each of which a pulse is sent out and received. The received echo is rectified on the indicator panel and the output is used to brighten the spot of the scope by modifying the cathode potential. Because of the retentivity of the CRO screen, it will show the location of all reflecting surfaces within sound range. This feature was included primarily for mine detection.

The switching unit is used to transfer the projector leads from the listening equipment to the echo-ranging equipment. Either short pulse or conventional echo-ranging equipment may be selected for comparison purposes. The functions of this switch would be incorporated in the automatic control equipment in a final design. Such a design, providing for combined listening and echo ranging in one system instead of two essentially independent systems, would also combine many of the features of the amplifier detector and indicator of the echo-ranging equipment with similar facilities in the listening equipment.

10.2.4 QBF Type Echo-Ranging System

The QBF equipment used for conventional echo ranging as installed on a submarine includes two cabinets in the stack, the lower one containing the driver, and the upper one containing the receiver. For use with the 692 sonar, a modification has been made to include a high-frequency pulse (50 kc) as well as the standard 25-kc pulse. This is selected by means of the toggle switches on the driver panel marked HI and LO and also by a switch in the terminal box to the left on top of the stack. An external power supply is connected to the driver through a plug at the lower right. The power input to this supply passes through the toggle switch in the terminal box. A loudspeaker is in the center on top of the stack.

A Sangamo range recorder is mounted above the stack. It has been stripped of its plotter and fire control mechanism and its circuit has been modified. The record consists of a short trace on each ping whose distance from the edge of the chart is proportional to range. This recorder was also used as a bearing indicator by supplying it with the output of either the sum or difference channel through an auxiliary amplifier. For this use the recorder scale was based on a search rate of 30 rpm. The travel of the stylus then corresponded to the change of bearing of the projector over 300 degrees of arc forward. While the projector is passing through the after 60 degrees, the stylus returns to the starting point. This method of recording bearing was found very useful in tracking torpedoes. The toggle switch mounted to the left of the recorder makes the selection between range and bearing indication.

10.3 CONCLUSIONS

The 692 submarine sonar, as an experimental system, has been found of value in determining the feasibility of features considered as requirements for the ultimate submarine sonar. In general, it can be considered that the 692 sonar has come through the development stage and is now ready for a Navy experimental program which will properly evaluate its capabilities. Some of the features, particularly those involving projector training and listening, have been studied by engineers in the field. The short pulse echo-ranging and mine detection equipment has not as yet been put aboard a ship. Design tests indicate, however, that the short pulse echo-ranging equipment will deliver an adequate signal and will accept and display whatever echoes are returned. However, the adequacy of its performance can be evaluated only at sea.

Chapter 11

THE CONTOUR BOTTOM SCANNER

Contour Bottom Scanner

The contour bottom scanner (Figure 1) is an experimental, low-power, echo-sounding scanning device undertaken by UCDWR to provide a rapid means of conducting hydrographic surveys necessary for amphibious landings and operations. The equipment operates at 116 kc and scans through an angle of 65 degrees either side of the vertical. The maximum slant range is 100 ft which, at a 50-ft depth, permits a strip approximately 175 ft wide to be surveyed. The equipment operates so as to "draw" a cross section of the bottom contour on the face of a cathode-ray oscilloscope [CRO] tube in the familiar plan position indicator [PPI] presentation although in this case the plane represented is vertical rather than horizontal. A survey speed of from 6 to 30 knots can be used, depending upon the CRO screen definition required.

11.1 INTRODUCTION

Many of the amphibious and landing operations conducted in the Pacific during World War II were in areas which, because of the lack of commercial activity in normal times, were inadequately surveyed. As a result it was necessary to make complete hydrographic surveys of advanced areas before they could be used for ships bringing in men and supplies. The wire-drag method commonly used in making these surveys was unwieldy and tedious in its operation. The contour bottom scanner was developed to provide an accurate, rapid, acoustical surveying method to supplement or replace the time-consuming wire-drag method.

A study of the problem indicated that the most feasible method was one in which means were provided to scan a band or ribbon of the ocean bottom at right angles to the path of the survey ship. Consideration was first given to the Model I FM sonar system[1] developed by UCDWR. Tests were made which demonstrated that the system could be used. However, it was felt that a less complicated pinging system would be equally satisfactory.

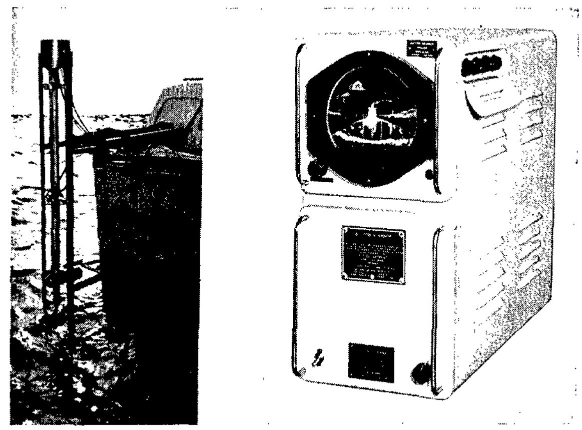


FIGURE 1. Contour bottom scanner.

The system which was visualized was one in which extremely short pulses of supersonic energy would be projected toward the bottom and the reflected energy received in the same Rochelle salt transducer. Provision would be made to mount the transducer so as to scan a strip of bottom at right angles to the survey ship's path. Rapid graphic plotting of the results was to be accomplished by the use of a cathode-ray oscilloscope.

A preliminary development model embodying these principles was built which operated at 86 kc. It was designed to survey a channel up to 50 ft in depth. The CRO indicator system provided a vertical PPI contour plot of the bottom area being scanned.

Following successful tests on the development model, a lightweight portable model operating at 116 kc from a 12-v d-c vibrator power supply was designed for use by small survey craft.

This portable model was not completed in time for use in the Pacific campaign, but was later used extensively in making hydrographic surveys.

11.2 EXPERIMENTAL DEVELOPMENT

11.2.1 Design Considerations

Depth Calibration. The fundamental design requirement was fixed by the Hydrographic Office request that the equipment be provided to survey a channel of the order of 50-ft depth. It was decided to rotate the transducer through a total angle of approximately 120 degrees (60 degrees either side of vertical). At a depth of 50 ft, the 120 degrees scanning angle provides for coverage of a strip approximately 175 ft wide at the bottom, and in this case the "slant range" varies from 50 to 100 ft. This establishes the requirement for a maximum slant range of 100 ft which is provided by a pinging rate of 24 per second.

Scanning Speed. A consideration of the geometry of the problem indicates that a transducer beam having a width of 15 degrees will cover the minimum area when the transducer beam is vertical. At a depth of 50 ft, this area will be 13 ft wide at the bottom. For design purposes, the effective area of the transducer beam, within the 6-db down points, has been considered a square having 13-ft sides. Since the beamwidth is 15 degrees, a minimum of 8 pings per 120 degrees sweep will cover the bottom without overlap, regardless of depth. Therefore, at least 8 pings per sweep must be made. The pinging rate has been fixed at 24 per second by the 100-ft slant range requirement. and therefore. the maximum scanning rate is 24 pings per second times 15 degrees per ping, or 360 degrees per second. Since each sweep is approximately 120 degrees, 3 sweeps per second, or 180 sweeps per minute, is the maximum sweep rate which will give full coverage of the bottom.

Indicator Definition. Although the transducer beam is 15 degrees wide, and for this reason complete "coverage" of the bottom is possible with echoes which are spaced 15 degrees apart on the screen of the indicator, it was believed advisable to limit the scanning speed so as to have not more than 3 degrees between adjacent echoes, in order to give a more detailed picture of the bottom contours. This limits the scanning speed to 24×3 or 72 degrees per second, rather than 360 degrees as mentioned above. This permits a maximum scanning speed of 36 sweeps per minute.

Survey Speed. It has been indicated that the area scanned in one full sweep (from right to left, or left to right) is 13 ft wide at the narrowest point (in the direction of travel) and about 175 ft long at right angles to the ship's course. If the maximum sweep rate is to be 36 sweeps per minute, the fastest forward speed that will give full coverage of the bottom is 9.8 ft per second. This is approximately 6 knots. A speed of 30 knots can be used if a 15-degree separation of echo traces on the CRO screen is acceptable.

It should be noted that the foregoing discussion is based upon the limiting condition of a 50-ft bottom. For depths appreciably less than this amount, slower scanning speeds and slower survey speeds are necessary in order to compensate for the reduction in the effective area of the transducer beam with a decrease in depth.

Conclusions. For a 50-ft depth of water, a scanning rate of 180 sweeps per minute provides full coverage of the bottom. A survey speed of 30 knots may be used under these conditions and this scanning speed provides echo traces which are spaced 15 degrees apart on the indicator. If a spacing of 3 degrees between echoes is required on the indicator, the scanning speed must be reduced to 36 sweeps per minute. In order to operate at this scanning speed, the ship's survey speed must be limited to 6 knots.

Because of the many uncertainties in connection with the use to which the bottom scanning equipment might be put, all equipments constructed were provided with a variable speed drive in the scanning mechanism so that a large variation in scanning speeds was possible. The various scanning speeds used in the tests of the equipment are indicated in the discussion of each test.

11.3 PORTABLE MODEL BOTTOM SCANNER

11.3.1 Overside Assembly

The overside assembly was designed for light weight and portability and was streamlined to

cut down water resistance and turbulance around the face of the transducer when under way.

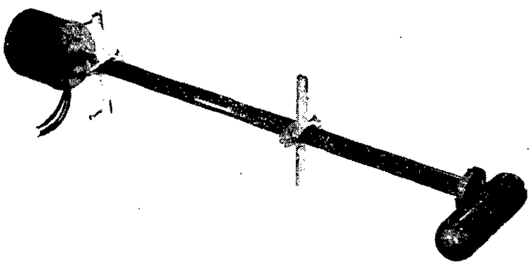


FIGURE 3. Overside column in retracted position mounted on MV *Torqua*.

Figure 2 shows the overside assembly and Figure 3 shows the column mounted on the MV *Torqua*. It can be seen by examining the photograph that the portable overside column

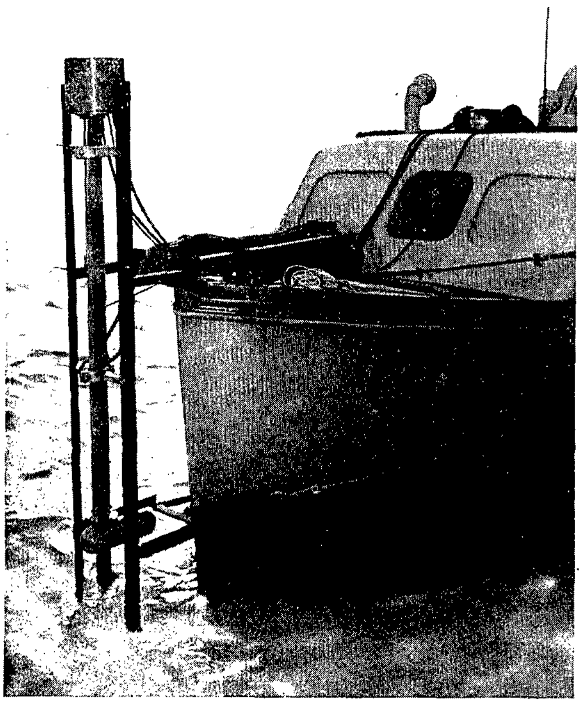


FIGURE 3. Overside column in retracted position mounted on MV *Torqua*.

consists of a length of 4-in. streamline steel Shelby tubing with a drum at the top and a streamline housing at the bottom. The streamline housing is made of $\frac{1}{16}$-in. Inconel and is divided near the center. The front end contains the scanning drive mechanism and is fastened to a flange at the lower end of the column; the

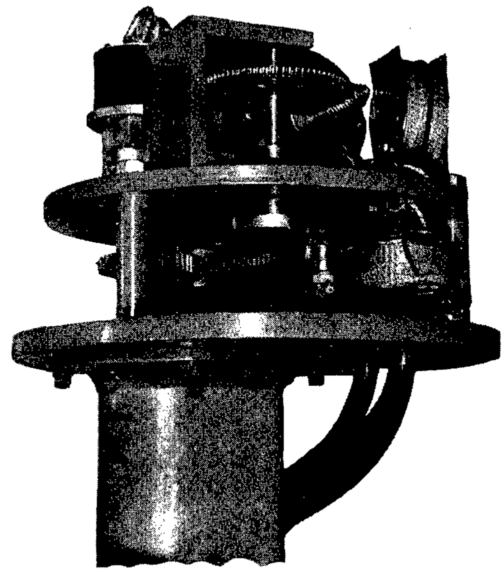


FIGURE 4. Scanning motor assembly with cover removed.

other end forms the housing for the transducer and is supported by a shaft from the front housing. The column is held in brackets that slide in tracks mounted on the bow so as to enable raising of the column when not in use.

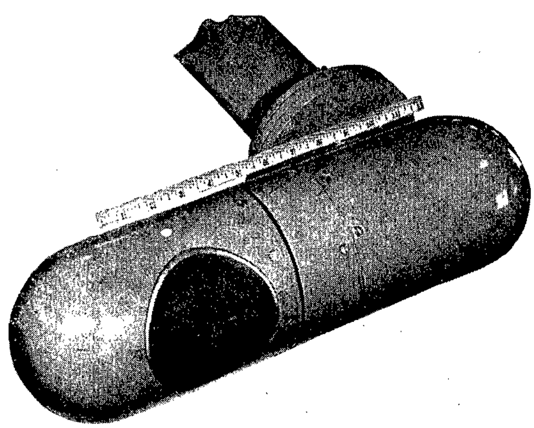


FIGURE 5. Streamlined housing assembly.

The drum at the top is a waterproof housing containing the scanning motor assembly, which consists of a 12-v d-c motor arranged to drive

a vertical shaft by means of a rack and pinion drive gear. Figure 4 shows the top assembly and shows the mechanism which translates ro-

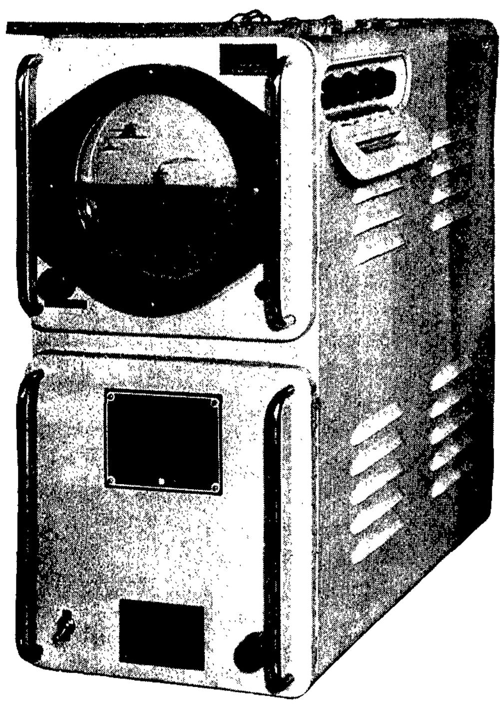


FIGURE 6. Electronic stack including indicator.

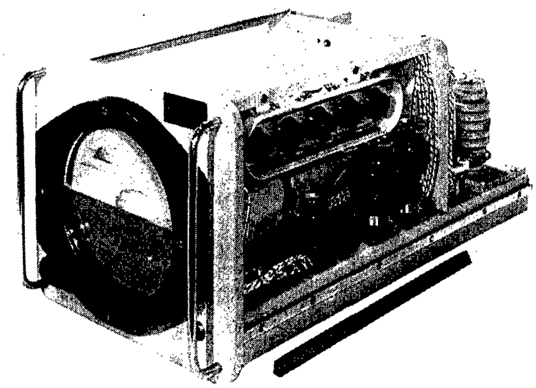


FIGURE 7. Indicator removed from the electronic stack.

tating motion from the motor into oscillating motion for the transducer drive shaft. The rack and pinion oscillate the drive shaft through a sweep of 130 degrees.

At the bottom of the vertical drive shaft a universal joint contained in the forward streamline housing connects the vertical drive shaft to the horizontal transducer drive shaft.

The transducer is enclosed in the rear streamline housing which is 5 in. in diameter and $7\frac{1}{2}$ in. long. This housing is made to oscillate through 130 degrees so that the transducer,

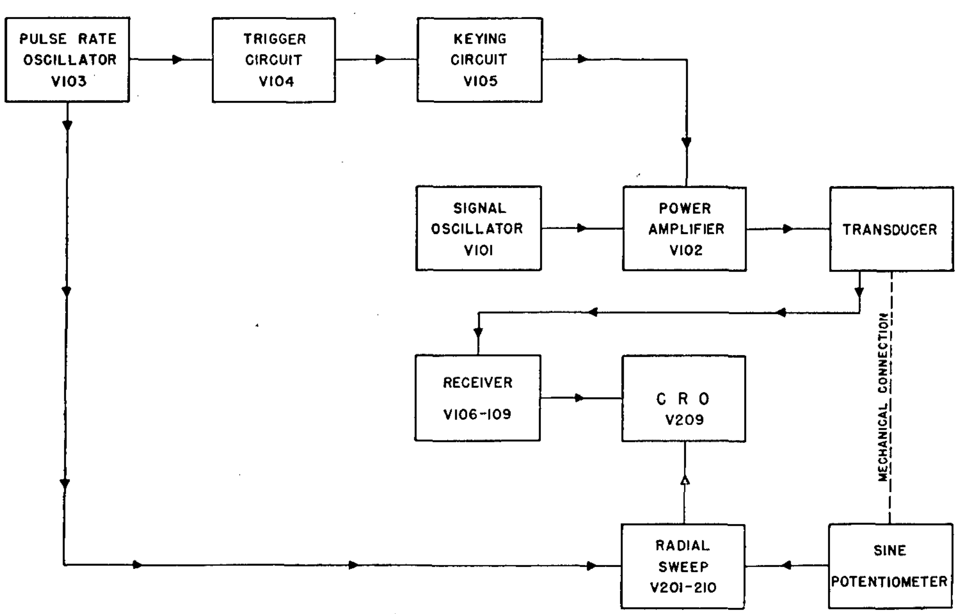


FIGURE 8. Simplified block diagram of contour bottom scanner.

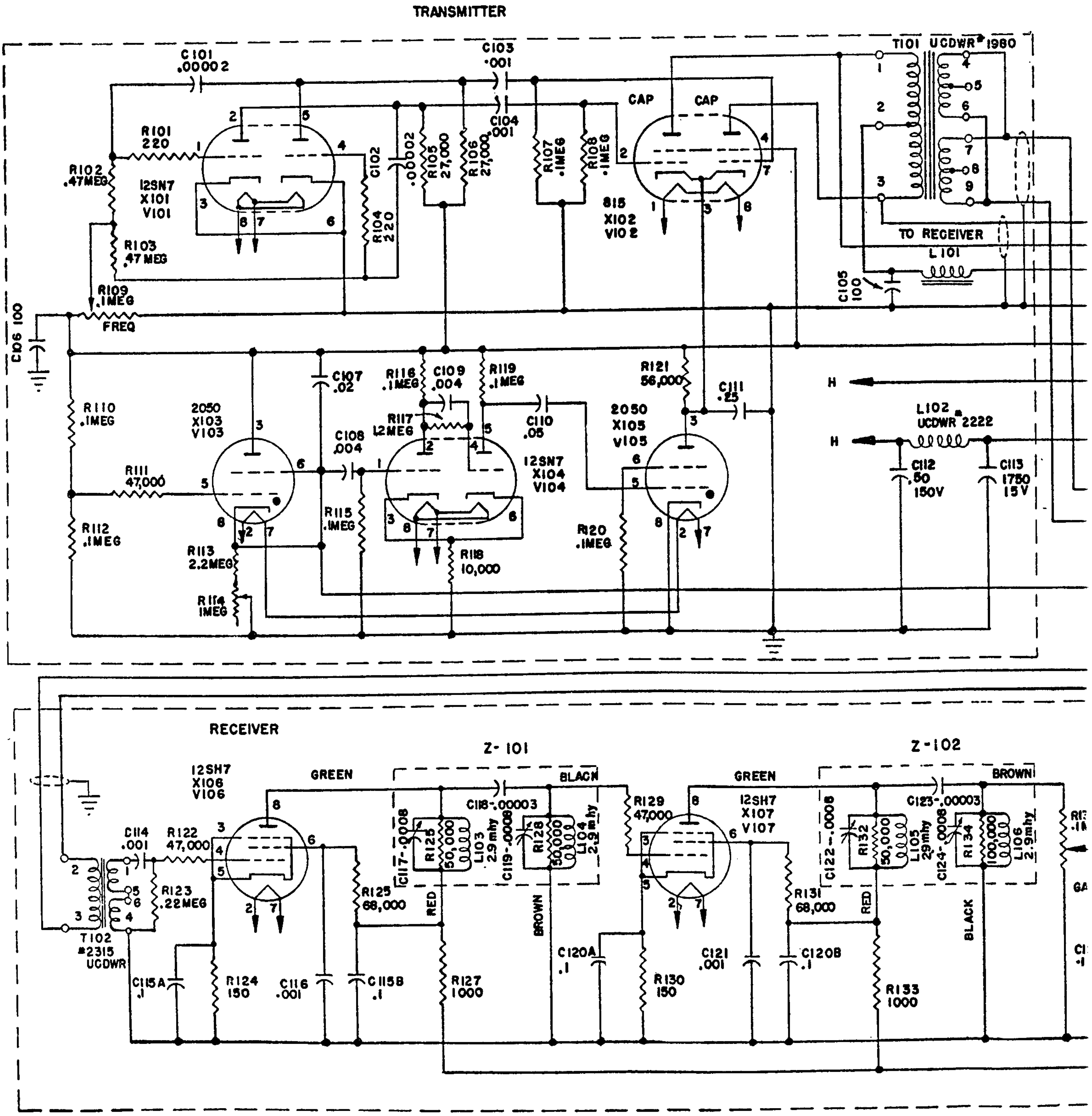


FIGURE 9. Transmitter and receiver wiring diagram.

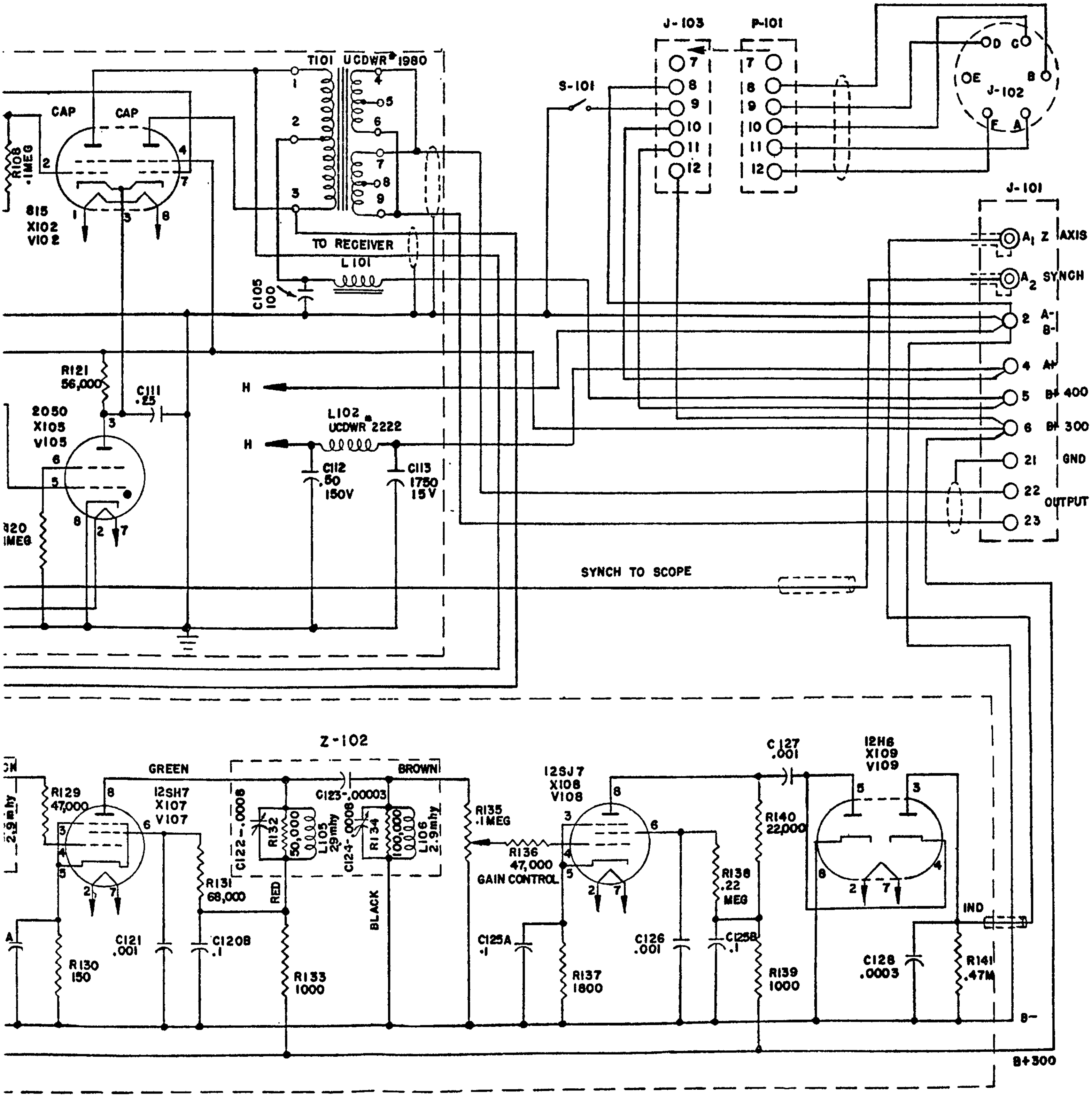


FIGURE 9. Transmitter and receiver wiring diagram.

facing downward, scans 65 degrees each side of vertical. Figure 5 shows the streamline transducer housing.

The sweep speed is controlled by adjusting a potentiometer connected in the armature circuit of the drive motor. By this method the sweep speed may be adjusted to exact speed necessary for full coverage at any forward speed.

11.3.2 Electronic System

The electronic system is housed in a compact double drawer cabinet 20 in. high, 10 in. wide, and 20 in. deep. Figure 6 is a photograph of the stack showing the indicator chassis in the top drawer and the chassis containing the transmitter and receiver in the bottom drawer.

The master switch and the receiver gain control are located at the bottom of the lower panel. The intensity, sweep amplitude, focus, and the vertical positioning and horizontal positioning controls of the indicator are at the upper right side of the cabinet under a small door as shown in Figure 6. The threshold control is located at the lower left of the screen, and a pilot light is located at the lower right. The CRO chassis is shown in Figure 7. The screen of the CRO is covered with a Lucite window 6 in. in diameter held in place over the face of the tube. The markings on this screen represent a cross section of the sky and sea, the water line being at the diameter. These markings are made for the purpose of enabling immediate identification by the observer. The lower half of the screen is marked with horizontal and vertical grid lines at distances representing 20 ft, the full scale being 100 ft. These lines enable measurement at a glance of the depth at different points along the bottom contour.

11.3.3 Screen Representation

The sweep starts at the center of the screen and the maximum sweep amplitude reaches the edge of the screen; this distance represents 100 ft. With the threshold control full "on" the radial line can be seen to sweep back and forth across the lower part of the screen between limits of 65 degrees each side of center. The bottom contour line will appear on the screen between these two radial limits at a position depending on the depth.

11.3.4 Theory of Operation

The theory of operation can best be understood by reference to the block diagram, Figure 8, and to the schematic wiring diagram for each unit.

Transmitter

The transmitter consists of five tubes; two 12SN7's, two 2050's, and an 815. One 2050 tube establishes the pulse rate and triggers a 12SN7 which limits the pulse length and causes the second 2050 tube to conduct. The second 2050 keys the final amplifier which is driven by the second 12SN7 operating as an oscillator. Figure 9 is a schematic of the transmitter and receiver.

Pulse Rate Oscillator. The pulse rate oscillator employs a type 2050 gas tetrode (V-103) in a relaxation oscillator circuit. This oscillator establishes the pulse rate and controls the trigger circuit through a pulse-shaping differentiating network (C-108 and R-115). The output of V-103 is a negative sawtooth wave which is generated by the charging and discharging of condenser C-107.

C-107 is charged through resistors R-113 and R-114 and as the charge increases, the cathode-to-grid voltage on V-103 decreases. When the cathode is depressed to the grid potential, V-103 conducts and discharges C-107. This cycle is repeated at a rate dependent upon the adjustment of the 1-megohm potentiometer (R-114) which controls the charging rate on C-107. The sawtooth voltage appearing at the cathode of V-103 is fed to the indicator for synchronizing purposes and is also fed to the trigger circuit.

The Trigger Circuit. Pulses from the pulse rate oscillator are fed through a differentiating circuit to the input of the trigger circuit which employs V-104, a twin triode 12SN7. The differentiating circuit (C-108 and R-115) changes

the sawtooth voltage wave into a succession of sharp positive pulses which are impressed on the grid of the first half of V-104. The time constants of C-109 and R-117, which connect the plate of the first section to the grid of the second section, control the trigger circuit and establish the pulse length at approximately 1 msec. This pulse is fed through the coupling condenser, C-110 to the keying circuit.

Keying Circuit. The keying circuit employs V-105, a 2050 gas tetrode in a modified relaxation oscillator circuit. The keying tetrode is connected so as to complete the cathode circuit of V-102, which is the power amplifier. The plate voltage of V-105 is applied through R-121 and the plate circuit, which includes C-111, is so arranged that conduction of V-105, which is initiated by the pulses from V-104, is terminated at the end of each pulse with the assistance of the discharge of C-110. Upon firing of V-105, the cathode of V-102 is brought to ground potential thus removing the high negative bias and permitting V-102 to function as an amplifier. The voltage drop across V-105 provides the necessary bias for operation of V-102 as a class AB_1 power amplifier.

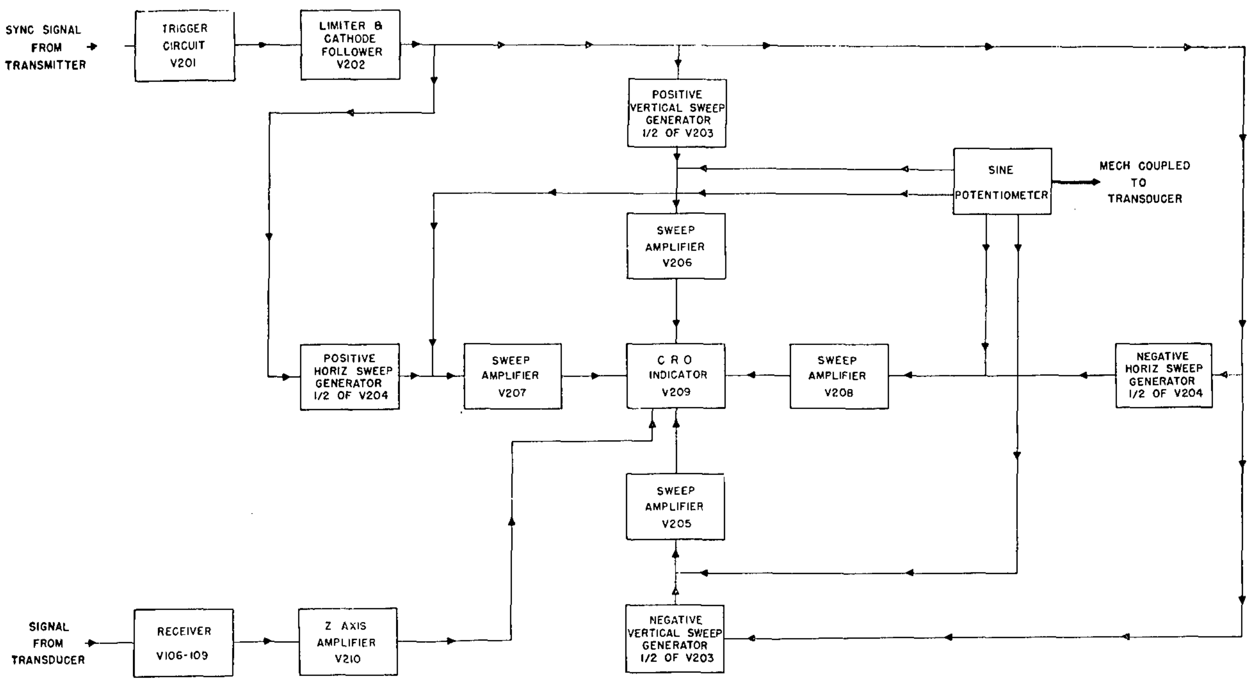


FIGURE 10. Block diagram of radial sweep circuit and CRO indicator.

RECEIVER

The receiver is mounted on the same chassis with the transmitter. The circuit for the receiver is shown in Figure 9. The receiver consists of four stages: two tuned band-pass stages and one untuned stage followed by the detector.

The input to the receiver is bridged across the primary of the transformer T-101 which couples the output of the transducer to the receiver. It will be noted that the transmitted signals appear directly across the transformer terminals.

The grid resistors R-122, R-129, and R-136 provide protection to each stage against overloading from the transmitted pulse. This is accomplished by the high negative bias produced by the voltage drop across the grid resistors. The RC constants throughout the receiver are established so as to provide quick recovery.

The two pentode (12SH7) amplifiers (V-106 and V-107) are coupled through a 116-kc band-pass filter (Z-101); and a similar filter (Z-102) couples V-107 to V-108 which is a 12SJ7 pentode amplifier. R-135 is the gain control and regulates the input level to V-108 which is in

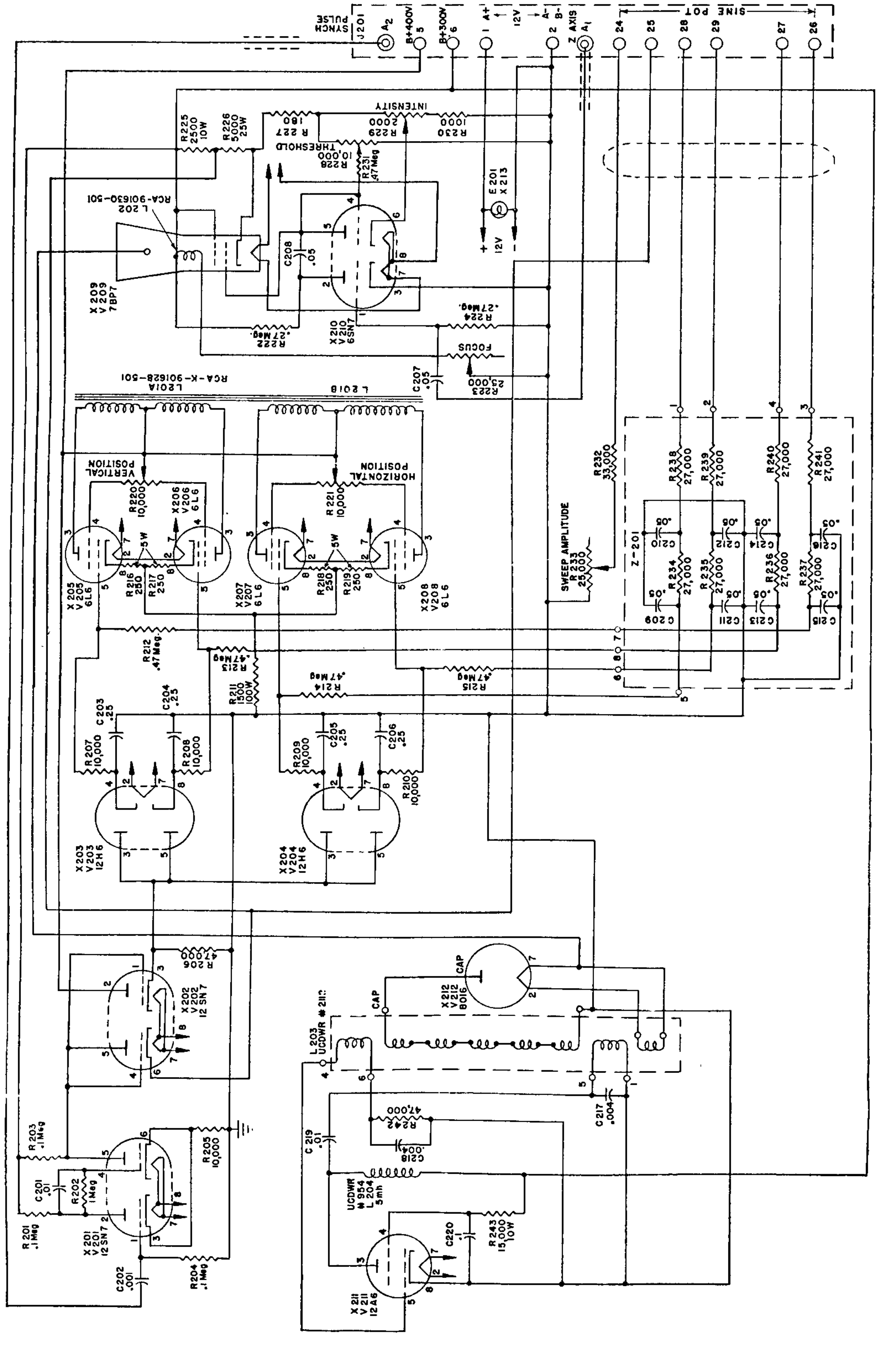


FIGURE 11. Schematic diagram of indicator circuit.

turn resistance-coupled to the detector (V-109) which is in twin diode 6H6. The negative half of the signal pulses are rectified by the second half of the tube and develop a voltage across the integrating circuit consisting of R-141 and C-128. The constants of this circuit are selected so as to match the pulse length of 1 msec. The positive half of the pulses are rectified by the first half of V-109. This serves to complete the diode detection circuit.

INDICATOR

The indicator contains a CRO tube and its usual controls (position, intensity, focus, and sweep amplitude) and also the operating con-

FIGURE 12. ER2-Z transducer with cover removed.

trols of the system (the threshold control, and the master switch). The indicator unit also contains its own high-voltage power supply, the necessary radial sweep circuits and z-axis amplifier for obtaining indication corresponding to the contour of the bottom. The operation of the indicator is shown in the block diagram, Figure 10, and the circuit is shown in Figure 11.

The cathode-ray tube (V-209) used is a 7BP7, a 7-in. tube with a long-persistence screen. The high voltage is supplied by an r-f oscillator, a 12A6 tube (V-211), in conjunction with a high-voltage step-up transformer L-203. The r-f oscillator operates at a frequency of 200 kc and its plate and regenerative feedback coils make up the primary of the step-up high-voltage transformer. The output of the secondary is rectified by V-212, an 8016 diode, and the 4,000 v is fed to the anode of the CRO (V-209).

The indicator includes a trigger circuit, a limiter, a cathode follower, and four sweep circuits. The trigger circuit, which includes V-201 (a 12SN7), initiates the charging of the four sawtooth generator condensers, C-203, C-204, C-205, and C-206. It receives its synchronizing pulses from the pulse rate oscillator in the transmitter (V-103) and triggers the start of the sawtooth through V-202. The first half of V-202 (a 12SN7) is connected as a biased diode and is used as a limiter. The second half is used as a cathode follower to couple the pulses to the sawtooth generator clamp circuits.

The sawtooth generators are two 12H6 twin

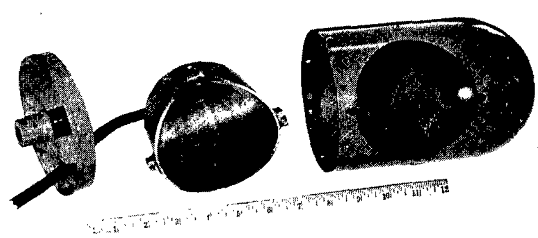
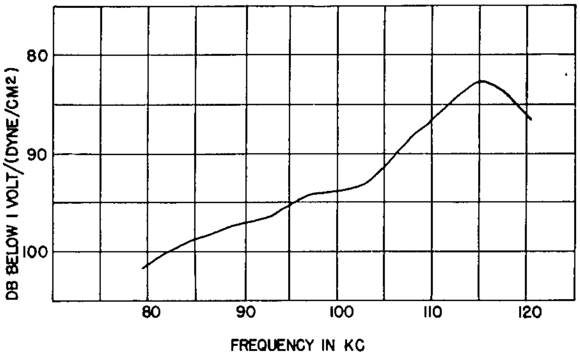
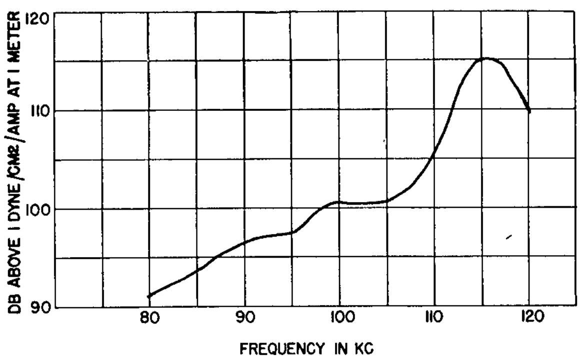


FIGURE 13. Disassembled view of transducer portion of streamlined housing.

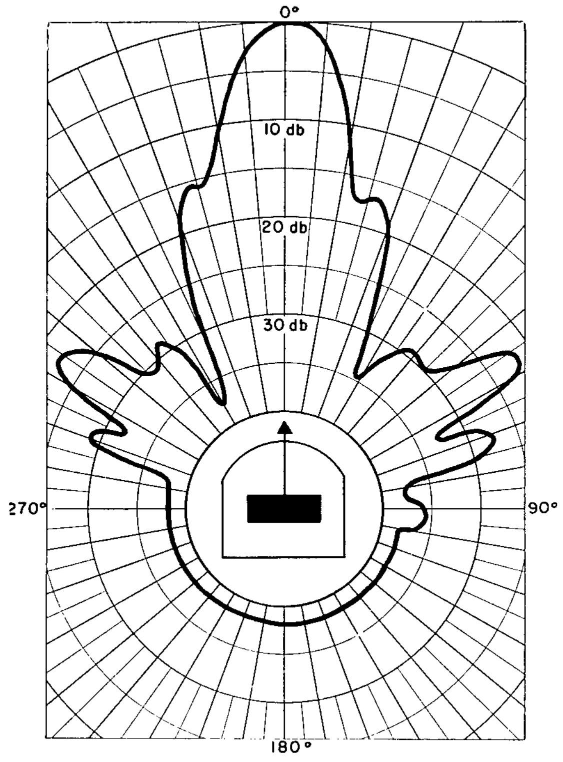
diodes (V-203 and V-204). The positive pulse, limited and controlled by V-202, drives all four plates of the diodes positive. This clamps the voltage applied to the four sawtooth generator condensers. The grid potential on each of the four 6L6 sweep amplifiers (V-205, V-206, V-207, and V-208) is controlled by the sweep generator condensers through the resistors R-207, R-208, R-209, or R-210. Since there is a low impedance between the cathode and plate when the plate is positive, the four diode cathodes will be brought up to the same reference potential as the plates by the pulse. At the end of the pulse, the diode plates are driven negative, allowing the condensers in the cathode circuits to discharge through the circuit including the resistor in the cathode circuit and the entire sine potentiometer network. Since the sine potentiometer network is energized through the



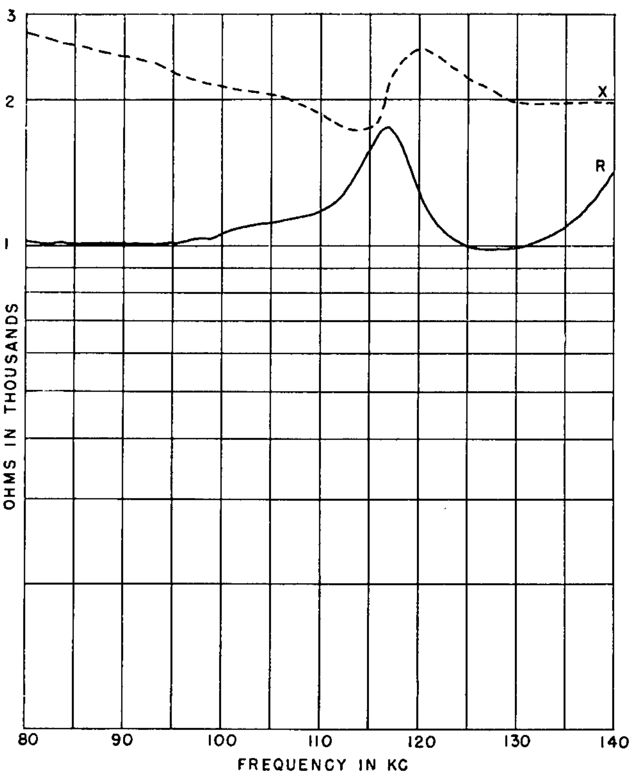
A. Receiver open-circuit frequency response.



B. Transmitter frequency response measured with constant current input.



C. Directivity pattern at 116 kc in a plane perpendicular to the crystal array and containing the fore and aft axis of the transducer mounting. The pattern in the vertical plane perpendicular to the fore and aft axis is essentially the same.



D. Complex impedance.

FIGURE 14. ER2-Z transducer characteristics.

sweep amplitude resistor R-233, the condensers will each discharge to a definite voltage depending both upon the total voltage impressed upon the sine potentiometer network and also

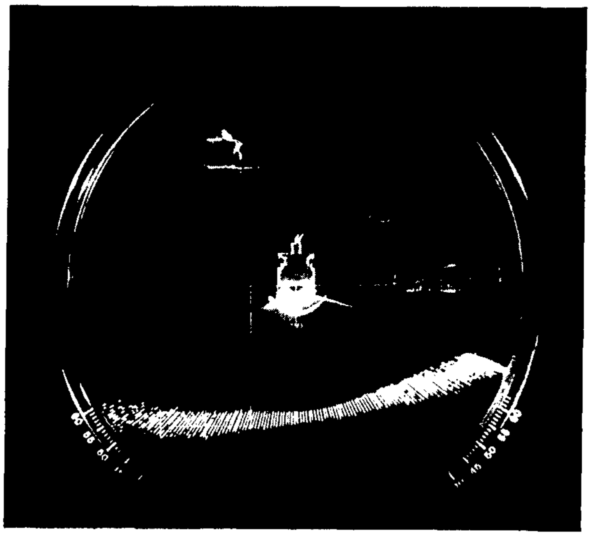


FIGURE 15. Photograph of indicator traces.

upon the orientation of the sine potentiometer brushes. Thus the four condensers will discharge at rates proportional to the sine, minus sine, cosine, and minus cosine of the sine potentiom-

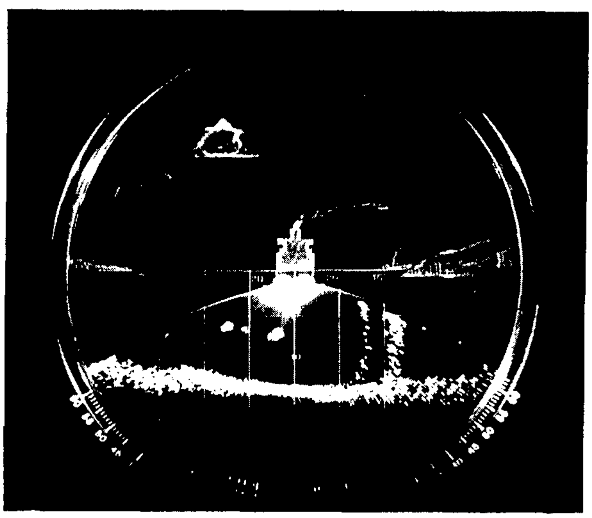


FIGURE 16. Photograph of indicator traces.

eter orientation. The grids of the four sweep amplifier tubes follow the condenser discharge rates and thus produce the radial sweep impulses in the CRO deflection coils which are connected in the plate circuits of the sweep amplifier tubes. The angular position of the transducer is thus resolved by the sine potentiometer into rectangular components, and these components are then used to control the direction of the outward sweep of the spot.

The four deflection coil drivers have large cathode resistors to increase their stability. Centering of the pattern is accomplished by the potentiometer R-220 connected between the screens of the vertical pair of the driver tubes and by another potentiometer R-221 connected between the screens of the horizontal pair. The tap connections of the two potentiometers return to the plate supply voltage.

The z-axis amplifier consists of a triode (the first half of V-210) which is a 6SN7 twin triode. The triode operates without bias, since the incoming signal from the receiver consists of negative pulses. The output of this triode is capacity coupled to the grid of the CRO tube through C-208. The grid of the CRO tube is shunted by a diode limiter (the second half of V-210 connected as a diode). The diode limits the maximum voltage which can be applied to the grid of the CRO. The intensity control R-229 establishes the cathode potential of the diode and thus regulates its action as a limiter. The threshold control R-228 establishes the normal bias on the CRO tube and thus regulates the zero signal intensity of the CRO spot.

VIBRATOR POWER SUPPLY

The power supply consists essentially of a Rauland-type V13K, ten-contact vibrator with its associated power transformer, rectifier tubes, filter circuits, and the added features of a delay tube and a safety tube.

The supply draws 23 amperes from a source consisting of two 6-v heavy-duty storage batteries in series and supplies 400 v at 200 mils and 300 v at 75 mils with approximately 67 per cent efficiency. It is of conventional design and therefore is not described in detail here.

TRANSDUCER

The transducer, UCDWR Type EP-2Z, which is shown in detail in Figure 12, is made of ADP

crystals and operates at 116 kc. It consists of a spaced array of 110 ADP crystals each 0.5 x 0.470 x 0.088 in. The crystals are cemented to the plane (inside) surface of the ρc rubber window. The crystals are connected in parallel with $\frac{1}{32}$-in. spacing between crystals. The array is approximately $3\frac{3}{4}$ in. in diameter. The ρc rubber window is bonded by a special bonding process to the inside surface of a $\frac{1}{8}$-in. stainless steel case 4 in. in diameter and $3\frac{1}{2}$ in. high which is then installed in the transducer streamline assembly, shown in Figure 13. On completion, two perforated Vinylite containers filled with silica gel were installed around the crystal array to keep the transducer free from moisture. Figure 14 shows the performance characteristics of the transducer.

11.3.5 Test Results

Several tests were made with the portable model aboard the MV *Torqua* and various bottom contours appearing on the indicator screen were photographed. In San Diego Harbor, the bottom contour around Ballast Point was photographed showing the steep incline near the shore. Around the sea side of Point Loma, a run was made through the kelp beds showing bunches of kelp in the water and long lengths of it growing up off the bottom from 30 to 40 ft high. A run was also made along each side of the submarine canyon near La Jolla showing the various inclines and ledges along the canyon walls. Still another run was made in shallow water over the rocky bottom in La Jolla cove.

Photographs that are representative of those taken during the above runs are presented in Figures 15 to 18. In these photographs, the scale is such that the distance from the center to the outside edge of the screen represents 100 ft. The horizontal and vertical lines are marked in feet and are spaced apart a distance representing 20 ft.

A scanning speed of approximately 15 sweeps per minute was used to insure good definition during most of the runs pictured. One picture is shown of bottom contours with a sweep speed of approximately 45 sweeps per minute for the purpose of comparison in screen definition.

The width of the bottom trace appearing on the screen is primarily dependent upon the ping length and the character of the bottom. However, it is modified by other factors such as angle of reflection and beamwidth, which accounts for the change in trace width as the sweep extends to either side.

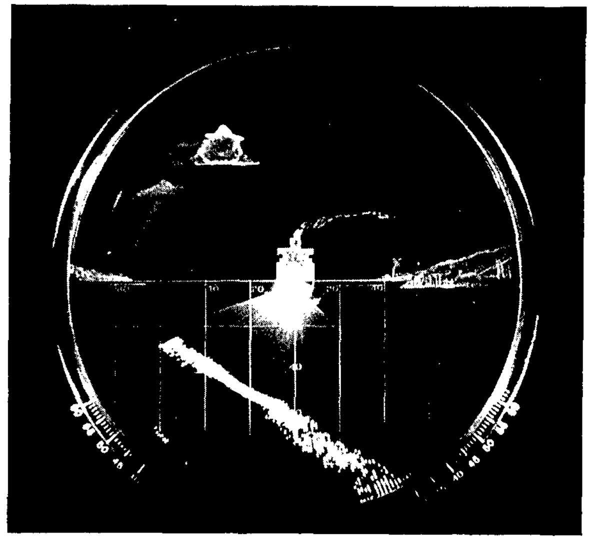


FIGURE 17. Photograph of indicator traces.

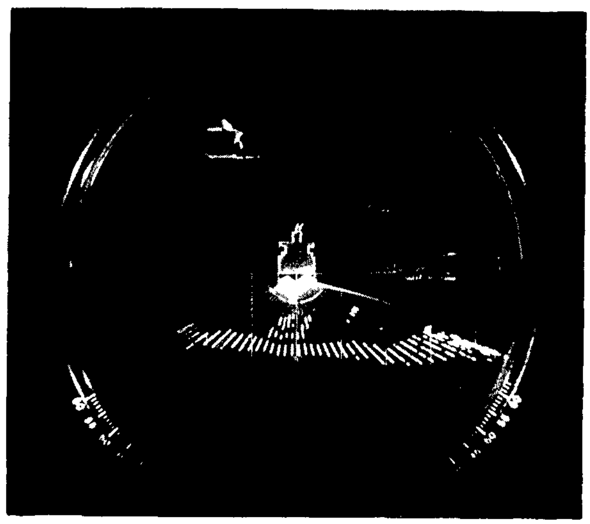


FIGURE 18. Photograph of indicator traces.

Figure 15 is a photograph taken during the run in San Diego Harbor around Ballast Point showing a sharp incline to the right from 50 up to 25 feet.

Figure 16 is a photograph taken during the run through the kelp beds on the sea side of Point Loma. The bottom at this location is about 50 ft deep with a 10-ft incline to the left. The photograph shows lengths of kelp growing up from the bottom 30 and 40 ft high. Figure 17 is a picture taken in La Jolla cove in shallow water 30 ft deep where the area is known to be rocky. A 20-ft pinnacle appears at a distance 20 ft to the left.

Figure 18 is a photograph taken at the fast sweep speed of 1⅓ sec per sweep, and shows the bottom at a 30-ft depth with some kelp 20 ft below the ship. The screen definition in this photograph is not nearly so good as that of the other photo taken at the 4-sec sweep rate; however, the definition is adequate for determining bottom contour and the height of any pinnacles.

11.3.6 Conclusions

Tests made with the portable model have shown that it is capable of producing a cross-sectional picture of the bottom within a slant range of 100 ft with an accuracy of approximately 2 per cent. The successful operation of this system at the higher frequency of 116 kc permitted the use of a smaller transducer, thus requiring only a lightweight supporting column and scanning mechanism. The electronic stack is also lightweight, and since both the scanning column and electronic system are operated with power from two 6-v storage batteries, the complete system is readily portable and may be used on small vessels.

The horizontal and vertical 20-ft divisions on the screen make it possible to read directly on the screen the position and size of any pinnacle or change in contour of the bottom.

The contour bottom scanner, together with a suitable hydrographic surveying technique, may possibly take the place of the wire drag method. This belief is substantiated by the results of tests which were conducted under the auspices of the Navy Electronics Laboratory in connection with the "Crossroads" project. During these tests, which were made in April 1946, the bottom scanner was used to complement the wire-drag method. The tests were very satisfactory, and rapid accurate data were secured concerning the shoals and other obstructions which had been located by the wire-drag method. It should be noted that the low forward speed and comparatively narrow widths of bottom covered are important limitations and must be considered in attempting to use the bottom scanner in competition with the wire-drag method.

11.4 PROPOSED DEVELOPMENT WORK

11.4.1 Investigation of FM Sonar System

During the early part of bottom scanner development some investigation was made of FM sonar system as applied to this field. It was intended at the time to carry along this work in parallel with the more portable pinging system. However, because of the possibility of using the portable system in reconnaissance work for amphibious warfare, it commanded the greater priority and required all available man-hours so the FM sonar investigation was temporarily shelved for the duration of the war.

Now that hostilities have ceased and the desirability of a portable system is not so pressing, continuance of the FM sonar investigation is highly desirable. For a lightweight portable bottom scanner the pinging system would be hard to surpass; however, without the need for portability, a successful application of FM sonar system to bottom scanning should be the real answer to a universal bottom scanner because it does not have the screen definition limitation of the pinging system and it has the further advantage of simplicity in changing ranges.

11.4.2 Roll Correction

The use of the bottom scanner in the "Crossroads" operation emphasized the need for auxiliary equipment to provide the proper correction for the effect of rolling of the survey vessel in heavy weather.

A number of possibilities suggest themselves. The simplest device might consist of a roll indicator mounted on the face of the CRO and giving continuous indication of the attitude of

the survey vessel. The level indicator which was developed by Columbia University for use with the Mark 10 (A/S) Projector in the form of an arc-shaped glass bubble tube might serve very satisfactorily.[2] If more accurate indications are required, the use of an airplane-type vertical gyro suggests itself. This gyroscope might be used only to give indication of survey ship's attitude, or the calibrated screen on the face of the CRO might be moved to correct for the survey vessel's position. More elaborate schemes in which a suitable gyro-vertical is used to correct the sine potential indication, or to stabilize mechanically the transducer by a superimposed rotation to correct for roll, are other possibilities.

GLOSSARY

ACG. Automatic control of gain.

ADE. Audible doppler enhancer.

ADP. Ammonium dihydrogen phosphate, crystal having marked piezoelectric properties.

AFC. Automatic frequency control.

A/S. Antisubmarine.

A SCOPE, A SCAN. A CRO-indicator depicting echo intensities by vertical deflections, and ranges by the position of these deflections on the horizontal trace.

ASDIC. British echo-ranging equipment. Letters derived from "Anti-Submarine Development Investigating Committee."

ATF. Automatic target follower.

ATT. Automatic target training.

AVC. Automatic volume control.

AVS. Anchored vessel screening.

BDI. Bearing deviation indicator.

BFO. Beat frequency oscillator.

BTL. Bell telephone laboratories.

CAVITATION. The formation of vapor or gas cavities in water, caused by sharp reductions in local pressure.

CHEMICAL RECORDER. An indicator which records range on chemically treated paper.

CRL. Compensation for range loss.

CRO. Cathode-ray oscilloscope.

CT. Control transformer in synchro system.

CUDWR. Columbia University Division of War Research.

CUT-ONS. Method of bearing determination from initial and final echoes obtained as echo-ranging beam is swept across the target.

DCG. Doppler controlled gain.

DG. Differential generator in synchro system.

DIRECTIVITY INDEX. A measure of the directional properties of a transducer. It is the ratio, in decibels, of the average intensity, or response, over the whole sphere surrounding the projector, or hydrophone, to the intensity, or response, on the acoustic axis.

EAR. Electronic aural responder.

EAS. Electronic automatic search.

ECHO REPEATER. Artificial target, used in sonar calibration and training, which returns a synthetic echo by receiving, amplifying, and retransmitting an incident ping.

EDI. Echo doppler indicator.

ERB. Echo ranging booster, combining ODN, RCG, RSF.

E/R RATIO. Echo-to-reverberation ratio.

FAIRLIE. H. M. Anti-Submarine Experimental Establishment, Fairlie, Scotland.

FM SONAR. Scanning-type sonar of UCDWR design using a continuous frequency-modulated transmission signal.

HUSL. Harvard Underwater Sound Laboratory.

HYDROPHONE. An underwater microphone.

HYDROPHONE EFFECT [HE]. Target noise as heard with a hydrophone.

MAGNETOSTRICTION EFFECT. A phenomenon exhibited by certain metals, particularly nickel and its alloys, which change in length when magnetized, or (Villari effect) when magnetized and then mechanically distorted, undergo a corresponding change in magnetization.

MATD. Mine and torpedo detection.

MTB. Maintenance of true bearing.

NLL. New London Laboratory.

ODN. Own-doppler nullifier.

PAL. Phase-actuated locator.

PIEZOELECTRIC EFFECT. Phenomenon exhibited by certain crystals in which mechanical compression produces a potential difference between opposite crystal faces, or an applied electric field produces corresponding changes in dimensions.

PING. Acoustic pulse signal projected by echo-ranging transducer.

PIP. Echo trace on indicator screen.

PPI. Plan position indicator.

PROJECTOR. An underwater acoustic transmitter.

QC. Standard Navy searchlight-type echo-ranging equipment using magnetostriction transducers.

QH. Navy designation for CR scanning sonar (originally applied to HUSL designs) employing magnetostriction transducers.

QL, QLA. Navy designation for FM sonar of UCDWR design.

RANGE RATE. Rate of change of range between own ship and target.

RCA. Radio Corporation of America.

RCG. Reverberation-controlled gain.

REVERBERATION. Sound scattered diffusely toward the source, principally from the surface or bottom and from small scattering sources in the medium such as bubbles of air and suspended solid matter.

ρc-RUBBER. A rubber compound with the same ρc (density $\times$ velocity of sound) product as water.

RLI. Right-left indicator.

ROCHELLE SALT. Potassium sodium tartrate ($KNaC_4H_4O_6 \cdot 4H_2O$) piezoelectric crystal used in sonar transducers.

RSF. Reverberation suppression filter.

SCANNING SONAR. Echo-ranging system in which the ping is transmitted simultaneously throughout the entire angle to be searched and a rapidly rotating narrow beam scans for the returning echo.

SEARCHLIGHT-TYPE SONAR. Echo-ranging system in which the same narrow beam pattern is used for transmission and reception.

SESE. Secure echo-sounding equipment.

SLC. Simultaneous lobe comparison.

SOD. Small object detector.

SONAR. Generic term applied to methods or apparatus that use SOund for NAvigation and Ranging.

SOUND CHANNEL. Rare condition, occurring when a negative velocity gradient overlies a positive velocity gradient in the water, whereupon the sound energy is confined between horizontal planes and thus may be transmitted over very long ranges.

SSI. Sector scan indicator.

SUPERSONIC FREQUENCIES. Range of frequencies higher than sonic. Sometimes referred to as ultrasonic to avoid confusion with the use of supersonic to denote higher-than-sound velocities.

TCG. Time controlled gain.

TDI. Target doppler indicator.

TRAIN. To rotate the transducer in a given direction about its axis.

TRANSDUCER. Any device for converting energy from one form to another (electrical, mechanical, or acoustic). In sonar, usually combines the functions of a hydrophone and a projector.

TVG. Time-varied gain.

TVL. Time variation of loss.

UCDWR. University of California Division of War Research.

USDAR. Underwater sound detection and ranging.

VBI. Vector bearing indicator.

WHITE NOISE. A uniform continuous noise spectrum.

XQHA. Navy designation for development model of azimuth scanning system employing the capacity commutator rotation principle.

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CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-20	The Trustees of Columbia University in the City of New York New York, New York	Studies and experimental investigations in connection with and for the development of equipment and methods pertaining to submarine warfare.
OEMsr-1128	The Trustees of Columbia University in the City of New York New York, New York	Conduct studies and experimental investigations in connection with and for the development of equipment and methods involved in submarine and subsurface warfare.
OEMsr-287	President and Fellows of Harvard College Cambridge, Massachusetts	Studies and experimental investigations in connection with the development of equipment and devices relating to subsurface warfare.
OEMsr-346	Western Electric Company, Inc. New York, New York	Studies and experimental investigations in connection with submarine and subsurface warfare.
OEMsr-30	The Regents of the University of California Berkeley, California	Maintain and operate certain laboratories and conduct studies and experimental investigations in connection with submarine and subsurface warfare.

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Subject*
NS-142	Basic improvement of echo-ranging gear.
NS-221	Silent echo sounding equipment.
NS-297	Detection of small objects by means of underwater acoustic devices.
NS-337	WCA conversion equipments, consulting services on, by Columbia University Division of War Research to BuShips (940) on its contracts NXsr-42164 (Task 9) and NXsr-65323 with RCA.

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ABSTRACT:

The work undertaken to improve the operation of the type of echo-ranging system is explained. The sonar systems, in which observations are made of underwater sounds radiated by target vessels, are defined generically as direct listening systems; those systems, in which the target is caused to become a secondary radiator, or reflector of acoustical energy are known as echo-ranging systems. Because only the activities of Division 6 are described, the report must not be considered as a text book on the subject of echo-ranging systems, but rather, as a reference work supplementing other publications. The report deals with circuits, training systems, Doppler applications, anchored vessel screens, small object detection, contour bottom scanners, and bearing deviation indicators for sonar and echo-ranging equipment.

DISTRIBUTION: Copies of this report obtainable from Air Documents Division; Attn: MCIDXD

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AIR TECHNICAL INDEX

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